Development of a Holistic Risk Assessment Methodology and a corresponding Computer Model for Landfill Leachate

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ABSTRACT

This thesis reports on the development of a holistic risk assessment methodology and a corresponding computer model for landfill leachate. Lack of a quantitative risk assessment methodology in a holistic format has prompted this research.

The two main aims of the study are:

- To investigate risk assessments regarding landfills and develop a quantitative methodology of risk analysis for landfill leachate in a holistic manner.

- To produce an electronic representation of the methodology in the form of a knowledge-base computer model.

In this study, a detailed review of the literature and available computer models on risk analysis for various environmental issues was undertaken. However, this review was narrowed down to focus on risk assessments particularly regarding landfills. The literature review revealed that there is no evidence of the existence of a holistic and yet quantitative risk analysis methodology. This was also found to be the case for computer models reviewed. All existing knowledge and gaps in the knowledge, which could be used as building blocks to assemble and produce a holistic framework of a risk assessment methodology (RAM) specifically for landfill leachate, were investigated and recognised.

The novel knowledge in this study has been generated in terms of adopting, adapting and furthering the existing knowledge with respect to risk analyses of landfill leachate. Where knowledge gaps exist, new concepts have been created to form the holistic RAM, thereby bridging the gaps. In addition, the RAM has been converted into a corresponding computer model, which can assist risk assessors and risk managers in executing risk assessment for a given landfill leachate in a quantitative and interactive manner. The RAM computer model produced was validated by employing a real landfill data provided by a company. A stage-by-stage comparison was drawn between this RAM application and the company's landfill risk analysis process, thereby identifying discrepancies between the two approaches.

The research work identifies boundaries of the internal relationship between various constituents within the RAM, and the external relationship of the RAM with risk control and risk management. Some examples of the main constituents of the RAM, which are individually developed in this research work, are listed as follows: 1) Baseline Study; 2) Hazard Identification & Categorisation; 3) Exposure Assessment & Exposure Quantification, 4) Concentration Assessment including toxicity assessment; 5) Migration Assessment; 6) Significance Assessment; 7) Uncertainty Assessment; 8) Risk Characterisation comprising Hazard Indices and Risk Quantification. The first four constituents together are referred to as Hazard Assessment in this study, and the last four as Risk Estimation.

The RAM, together with a corresponding computer model, is a novel development, in that no system has utilised this modern risk analysis concept before. The RAM has been designed in such a way that it can be applied to landfill leachate using a novel three-risk-theme approach. These three themes are 'worst case', 'most likely / mean' and 'least bad' scenarios of risk. A methodology, accompanied with a corresponding computer model, now exists for quantifying risk analysis of landfill leachate in a holistic format. This modern risk analysis approach addresses the piece-meal approach that has been employed to landfills to date.

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Chapter 1

INTRODUCTION

In the context of potential of environmental pollution, this introductory chapter mentions the position of landfill option in the waste management hierarchy, which is widely accepted. This chapter establishes that despite high pollution potentials, generally landfilling is still the most applied waste management option and particularly in the UK. Risk analysis is described as a tool to manage landfills in an environmentally friendly and sustainable manner. Risk assessment is also highlighted in the perspective of environmental legislation.

1.1 Landfills

With the advent of industrial revolution, ever since faster growing human populations and cities, and increasing economic growths at national and global levels, ever more amounts of wastes began to be generated and still are. These wastes include industrial, commercial and domestic waste streams. For instance, in the UK, 240 MT Controlled Wastes per annum and 190 MT Uncontrolled Wastes per annum are produced (DoE and the Welsh Office, 1995a). These figures imply every nine months there is enough waste only in the UK alone to fill Lake Windermere (DoE and the Welsh Office, 1995b). Unfortunately, the waste production is still on the increase in the UK (Davies, 1999; DETR, 2000; Cabinet Office, 2002; DEFRA, 2003; 2005a; 2005b). Even if wastes are reducing at a regional level in some cases (Scottish Executive, 2004), the transport of waste from the point of production to recycling facilities and outlets can outweigh the 'green' advantage thereby rendering the initiatives in those regions overall unsustainable. For instance, it has been reported that the North East's waste in the UK is being driven as far away as Wales for recycling (Ewen, 2005). Moreover, waste is the inescapable outcome of the activities which characterise human society; indeed in one sense it is an indicator of the health of modern economy (Tromans and Stiles, 2004). In summary, it can be safely said that no matter how high we move up the Waste Hierarchy illustrated in Figure 1.1 below, there will always be some waste left for landfills. This is elaborated further in the latter part of this section.

Sustainable waste management simply means managing waste by prioritising in the manner outlined in the Waste Hierarchy, which is shown in Figure 1.1 below (SEPA, 1999; DETR, 2000; Wilson, 2000; DEFRA, 2005a; 2005b). This implies waste prevention is the topmost priority, if possible. The other priorities in descending order are reduction; reuse; recovery via recycling, composting, energy; and disposal, which also includes landfilling. However, most of the waste produced, particularly in the UK is generally disposed to landfills (DETR, 2000). Another fact is also noteworthy in the Hierarchy is that landfilling is not only strictly at the bottom of the list but also partly constitutes the 'Recovery' category which is prior to the 'Disposal' group of waste management options.

Figure 1.1: The Waste Hierarchy

PREVENTION

REDUCTION

RE-USE

RECOVERY

- Recycling
- Composting
- Energy (recovered from the waste incineration, landfill gas combustion)

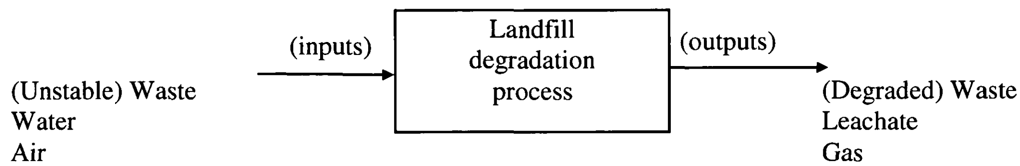
DISPOSAL

- Incineration without energy recovery
- Landfill without gas energy recovery

Waste disposal to landfills, in general, is an easy and cheap waste management option but it raises environmental concerns. During the process of waste degradation, landfills produce waste products in three phases (Figure 1.2). These are:

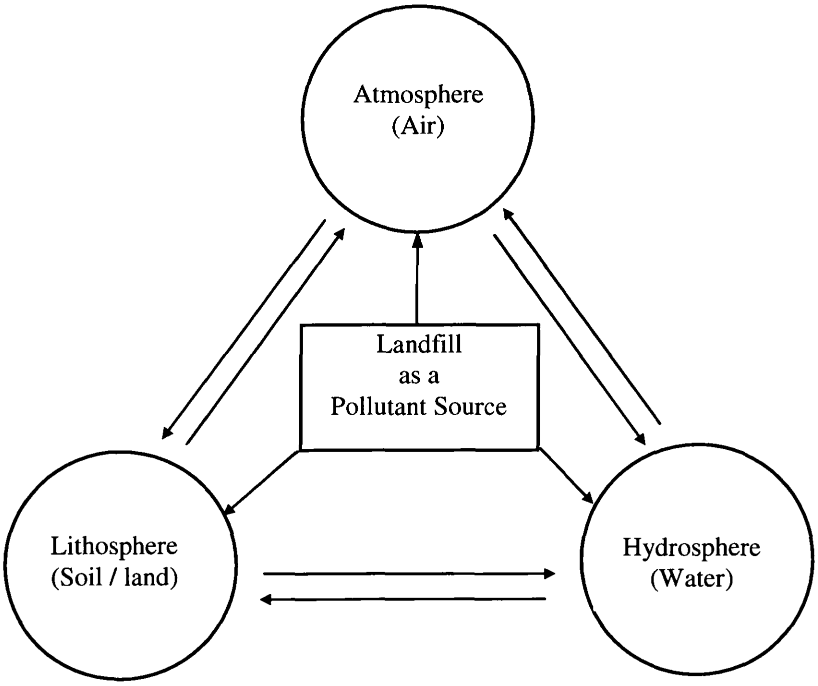
- Solid (i.e. more or less degraded waste);
- Liquid (i.e. leachate, which is water polluted with wastes); and
- Gas (usually referred to as landfill gas).

Figure 1.2: Inputs and Outputs of a Landfill Degradation Process



Further, landfills and their above stated waste products have the potential to pollute the three principal environmental media – the atmosphere, the lithosphere and the hydrosphere (Figure 1.3, Butt and Oduyemi, 2003; adapted from Moriarty, 1993). Such pollution will be transmitted through these media and will impact, either directly or indirectly, upon human, the natural environment (including aquatic and terrestrial flora and fauna) and built environment (EHS, 2001). Thus, landfills do not only produce pollutants in the three phases listed above but directly pollute non-living environmental receptors. That is, land, air and water and thereby living environmental species. This pollution potential necessitates that hazards and risks of landfills be assessed and managed to guard the environment and its species from landfill hazards. Moreover, risk assessments help to optimise site design, minimising capital expenditure whilst ensuring adequate environmental protection thereby satisfying the 'sustainable development' philosophy (SLR Consulting, 2004; DEFRA, 2004).

Figure 1.3: Three Principal Environmental Media and Fundamental Pathways for (Landfill) Hazards to Travel through.



On the other hand, the Waste Hierarchy has been presented in order to reduce waste amounts that are disposed of at landfills. However, its practicality is not and can not be 100%. For instance, waste production can not be reduced to zero in every scenario. Commodities can not be reused and / or recycled all the time e.g. paper after recycling a number of times becomes non-recyclable as paper fibre deteriorate every time it is recycled. Every waste can not be composted or incinerated. Even the incineration of wastes leads to other wastes (e.g. ashes) being generated though in much less amounts, which generally end up in landfills. Thus, landfills are inevitable. To be more exact, the number of landfills may be reduced but there can not be a 'no landfill at all' environment.

The concept 'out of sight' or 'out of mind' regarding waste itself and landfilling is not applicable any longer. To achieve the maximum protection of the environment against the hazards associated with landfill sites all potential hazards should be identified and the risks associated with them assessed. Risk assessment, a vital tool for environmental management, is increasingly being employed to landfill sites either yet to be built or under operation and also to completed and closed landfills (Kent County Council, undated; Environment Agency, 1997a; 1999; 2003). In summary, risk assessment and management is the only viable way of maximising protection of the environment against hazards associated with landfill sites.

1.2 Risk Assessment (RA)

Environmental awareness and concerns of the public over potential environmental threats posed by anthropogenic activities have grown rapidly towards the end of the twentieth century. This has happened not just in the UK, but also world-wide. In a book entitled 'This Common Inheritance' (DoE, 1990) it is written:

> *"Where the state of our planet is at stake, the risks can be so high and costs of corrective action so great that prevention is better and cheaper than cure. We must analyse the possible benefits and costs of both action and inaction."*

The analysis and management of risk and the mitigation of hazards have recently become very important due to the greater complexity of systems of all kinds and the increased potential for disasters on a global scale. World-wide, risk assessment legislation and methods have developed rapidly in the past 10 years (SCEG, 2003). People have become much more concerned about risks to health and the environment and are requiring answers, not only for the present generation, but also for generations to come (which is the essence of the concept of 'Sustainable Development'). There are many questions regarding the safe and efficient use of resources in addition to environmental concerns, which generally fall within the province of risk assessment and management. Also, effective risk management including mitigation of possible hazards have become a high priority area for governments. Moreover, various risk analysis methods are not being developed for and applied only to landfills but also other waste management practices including incineration, composting, land-spreading, sewage sludge and sewage discharges (Saffron, et. al., 2003).

The UK legislation has been increasingly supporting and guiding sustainable environmental management in all areas through a series of regulations. Moreover, environmental concerns and issues along with environmental legislation are already heading towards globalisation. Examples of such legislation are:

- Waste Management Licensing Regulations (SI, 2005; 1994a);
- EC Directive on Groundwater (EC, 1980) and Groundwater Regulations, (SI, 1998);
- EU Directive on IPPC (Integrated Pollution Control and Prevention) (EU, 1996);
- EC Directive on EIA (Environmental Impact Assessment) (EC, 1985);
- Environmental Protection Act, 1990;
- Environment Act, 1995;
- Water Framework Directive (EC, 2000);
- Landfill Directive (EC, 1999) and Landfill Regulations (SI, 2002);
- Strategic Environmental Assessment (SEA) Directive (ODPM, 2003; Scottish Executive et. al., 2005); and
- EC Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora (the Habitats Directive) (EC, 1992)

Having realised the significance and effectiveness of risk assessment in environmental management, the environmental legislation has started to impose risk assessment as a legal requirement (Environment Agency, 1997a; 1999; 2003a). For instance, for the protection of groundwater from landfill leachate, a risk assessment requirement has been legislatively introduced in the UK since 1st May 1994, through Regulation 15 of the Waste Management Licensing Regulations 1994 (transposed from EC Directive on Groundwater Protection (SI, 1994; 2005; Environment Agency, 1997a; 1999; 2003a). The Landfill Directive (EC, 1999) is implemented in England and Wales through the Landfill Regulations (SI, 2002), made under the Pollution Prevention and Control (PPC) Act (England and Wales) 1999. The equivalent legislation, which is called Landfill (Scotland) Regulations, has come out in Scotland (SSI, 2000; SSI, 2003; SEPA, 2005a; 2005b). An equivalent legislation is anticipated in Northern Ireland. Similarly, the advent of the Water Framework Directive (EC, 2000), which has been transposed into

UK legislation, pushes boundaries of protection of environmental receptors beyond just groundwater to surface waters and dependent ecological systems. That means a much more integrated approach is required. The Habitat Directive brings legal obligation to combat hazards in order to guard and enhance natural habitats and wild fauna and flora (EC, 1992). Thus, the environmental legislation is not only growing in the context of globalisation and strictness but also in terms of becoming more strategic and holistic.

In the literature review and the investigation of current computer models regarding risk assessment (discussed later in detail in Chapter 3 and Chapter 4, respectively), it is established that a risk assessment methodology does not exist in a holistic format for landfill gas, leachate or degraded waste. Also there is no holistic computer model of such a methodology, as the former have to exist beforehand to give birth to the latter. However, in this study landfill gas and degraded waste are not the focus but landfill leachate. This research project identifies a number of knowledge deficiencies in current risk analysis approaches. These knowledge gaps are attempted to be bridged to various possible degrees within the scope of the project. The work leads to a more holistic risk analysis methodology, which is accompanied by a corresponding computer model. *The definition of the term 'Holistic' implied in this document is described in the end of Section 3.1 of Chapter 3 on page 30.*

Chapter 2

THE SCOPE AND METHODOLOGY OF THE RESEARCH STUDY

This chapter indicates, with examples, that terminology regarding risks vary both in themselves as well as in their meanings. Parts of risk assessment and management that are to be addressed in this research study are outlined. Aims and objectives of the study are also listed. The chapter considers the classification of unlimited numbers of possible scenarios of landfills into comprehensive groups specifying which of these scenarios are addressed in this study, how and to what degree. Following this, there is a section on the remit of the Risk Assessment Methodology (RAM) and computer model developed in this project. At the end, the chapter describes the research methodology, which is used to carry out this project.

2. 1 Terms Used in Risk Assessment and Management

There are variations in vocabulary regarding risk assessment and management in the literature. In some cases different terms are used to imply the same meaning whereas in others the same terms have been found to mean different concepts. One reason for this, probably, is that the 'risk' discipline has and is being evolved in different parts of the world in a piecemeal manner and also in different contexts such as finance, environment, health, politics. Some examples of variations in both terminology and meanings are stated as follows. The term 'risk assessment' is also called 'risk analysis' in some documents (e.g. Molak, 1997), and effectively there is no difference between the two. They imply the same and thus are interchangeably usable. The term 'risk management' implies more of 'risk control' implementation in some documents (e.g. DoE, 1990) while in others it is considered as a whole process from hazard assessment through risk assessment to risk reduction to acceptable levels (e.g. CIRIA, 2001; WDA, 1994). Another example, is the term 'toxicity assessment', used in some publications such as CIRIA, 2001. In this study, hazard concentration assessment is applied instead as this would cover not only toxic effects on living receptors such as humans but also adverse influences on non-living targets like groundwater and rivers. The reason for this is that non-living receptors are not likely to develop toxic affects such as cancer. Such receptors would rather be a matter of whether they are polluted or not and if they are, then to what degree compared to the thresholds / control limits.

Thus, the term risk management can be defined as the whole process in which risk is estimated and decisions are made to accept a known or assessed risk and / or the implementation of actions to reduce the consequences or probabilities of occurrence of unwanted consequences (WDA, 1994; CIRIA, 2001; Kempfer, 2002). In this research project this approach of risk management has been applied, in which hazard assessment and risk assessment are seen as parts of (or in mathematical terms sub-sets to) risk management (see Figure 2.1). In summary, the project deems hazard assessment as a part of risk assessment whose outcome is used as input to risk estimation to complete the process of risk assessment / analysis. And later on, the output of risk assessment is to be employed as input to risk reduction thereby completing risk management process, as shown in Figure 2.2. *Thus, one of the objectives of this research study (as mentioned below in Section 2.2.2) is to streamline risk-related terminology and their implications.* It should be noted that the main focus of the study is the development of the hazard assessment and risk estimation parts of the risk management of landfill leachate. The research study excludes the risk reduction part. *However, definitions and details on these parts and their sub-parts are laid down in Chapter 5 where the development of a holistic methodology on risk analysis comprising these elements is discussed.*

It is worth noting that there are two approaches to risk analysis; the first is a hazard assessment and second is a full risk assessment, which exceeds the hazard assessment in terms of estimating the risks in order to assist establishing risk control options. A hazard assessment provides no estimate of probability that a harm will or can occur but just an indication of the potential of the harm. Risk measurement or estimation is that stage which looks into the likelihood or probability of occurrence of harm(s). Thus, when a risk estimation aspect is added on the top of the hazard assessment, the whole structure then becomes a full risk assessment, as illustrated in Figure 2.2. (ICE, 1994; Erskine, 1997; CEFIC, 1999; CIRIA, 2001; Kempfer, 2002).

Figure 2.1: Relationships between Hazard Assessment, Risk Assessment and Risk Management

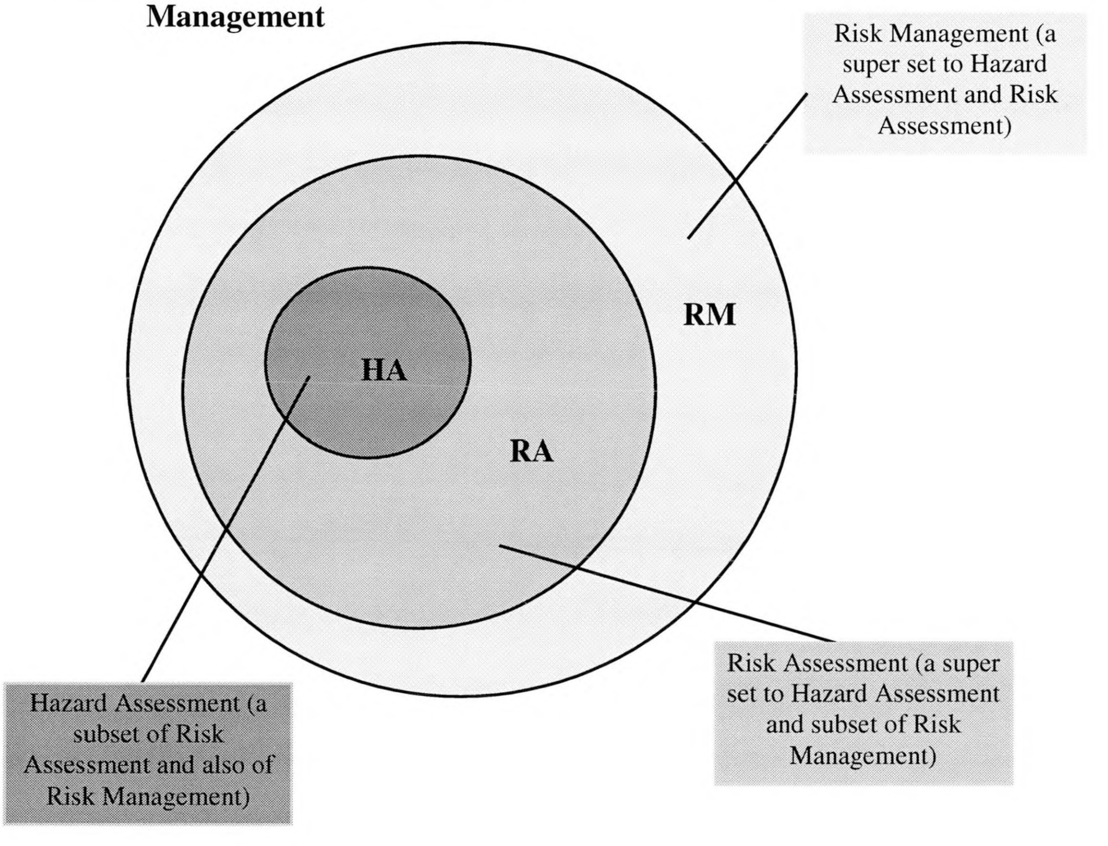
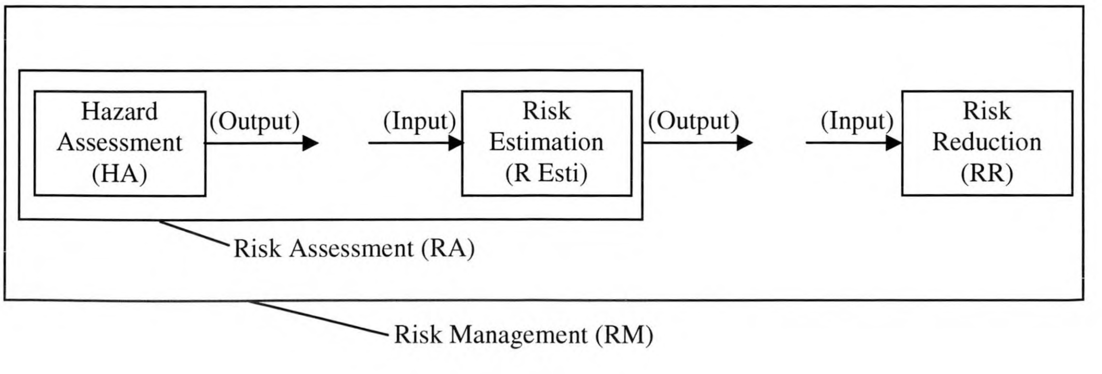


Figure 2.2: Main Parts of Risk Management



2.2 Aims and Objectives

2.2.1 The Aims

This research project has two aims, which are listed below:

1. The first aim of the research project is to produce a quantitative methodology of risk analysis for landfill leachate in a holistic format. In other words the aim is to develop such a concise and general risk assessment methodology for assessing risks posed by landfill leachate, that it could be made applicable to any type of landfill systems and scenarios.

2. The second aim of the project is to produce an electronic presentation of this methodology, that is a corresponding knowledge-base computer model (specifically for landfill leachate) that will also be holistic like the methodology.

2.2.2 The Objectives

The aims stated above are achieved by the objectives, which are listed below. More details on these objectives are provided in Section 2.5, which addresses the 'Research Methodology'.

- To collect together available and relevant information regarding characterisation of a landfill site and existing control strategies.

- To carry out a literature review, in particular in relation to:
    - hazard indices for non-carcinogenic hazards;
    - risks for carcinogenic hazards; and
    - How the two can be combined.

- To streamline different terminologies and their implications used in relation to risk.

- To further evaluate existing and proposed environmental legislation and determine critical / control levels of hazards.

- To outline an overall framework indicating all likely parts and sub-parts of the Risk Assessment Methodology (RAM) indicated in the aims above.

- To indicate benchmark sources, values and approaches, if standards are not suggested or dictated by, for instance, environmental legislation. Examples of such benchmark sources are SEPA, 2005a; EPA, 1997a; 1997b; 1997c.

- To establish the interconnections between the following:
    - baseline study,
    - hazard identification,
    - exposure assessment,
    - concentration assessment,
    - hazard indices, and
    - risk quantification.

- To translate the modules indicated above into a knowledge-base computer model.

- To test the knowledge-base computer model.

- To prepare and embody some databases in the computer model, for instance, List 1 and List 2 substances of the Groundwater Directive.

- To establish some methods of measurement of different parameters such as leachate quantity, precipitation, interception.

- To study the LandSim computer model and find out how some relevant aspects of the software can be useful in the computer model of the project.

- To investigate other computer models as well in order to establish their limitations and degree of holistic nature they have.

2.3 Landfill Scenarios

There is an indefinite range of scenarios with landfills. All these possible scenarios have been categorised into groups. These groups are listed and described below. Although the groups are definite in number, the scenarios themselves can be a lot more than the number of these groups. This is because scenarios can be any combination of any characteristics from these groups. Moreover, each group itself has more than just one scenario possible. These groups and scenarios are addressed to appropriate levels in the development of the RAM and the corresponding computer model as explained below. However, it is not possible to address all scenarios to full scale in this research project.

2.3.1 Post-, In- and Pre-Operation Phases of a Landfill

A given landfill being assessed may be in any one of the following three stages (ESM&P, 2002; Environment Agency, 2003b):

1. Pre-operation (for instance, design and / or planning stage),
2. In-operation, and / or
3. Post-operation (for example completed / or closed).

Every single landfill may not necessarily be just at one of these stages altogether at one time, but any combination of these three stages at the same time is possible. For instance, a given landfill is about to finish its current capacity, and its extension is undergoing planning and / or construction; a portion of a landfill is completed and closed while other portion is still taking wastes.

For the simplicity of a risk analysis process in this study, the three phases have been converted into two by merging the in-operation phase with the other two as follows. Suppose a landfill has three parts, one completed and closed (i.e. post-operation stage), one in planning or construction stage (i.e. pre-operation phase) and yet one part of a landfill is in operation. Furthermore, suppose that a portion of the in-operation part is active while other is not. For instance, one or two cells are being infilled with wastes while the others are being prepared to take wastes in future. So in the RAM developed in this research project, the portion of the given site taking waste (i.e. active in deed) is seen as the post-operation part of the landfill site and the rest as pre-operation one. This way, a landfill site altogether would be either in post-operation stage or pre-operation phase or maybe both. If both phases prevail then the risk assessment process has to be iterated twice. First for the post-operation portion and then second time for the pre-operation.

2.3.2 Time – Past, Present and Future.

This is discussed from two perspectives which are risk assessment items as individuals and risk analysis overall as a single entity. The three phases of time i.e. past, present and future can be considered for each and every item of the RAM. For instance the geological characteristics of a given site may vary over time. Chemical properties of earth materials may change and consequently the rates of cation exchange reactions after the wastes have been there for a while. Similarly, from the point of view of infilled wastes, the quality of leachate will vary with time as the wastes degrade. The groundwater level fluctuates with season / time.

Apart from risk analysis parameters as individuals (indicated above), to consider a risk analysis process overall, the future aspect of time can be accounted for in steps of years like 3, 5, 10, 30, 50, etc. The LandSim (discussed in Chapter 4) also allows for intervals in years. The future aspect is useful not only when a landfill is already existing but also when a landfill is yet to exist or pre-operation stage. For the present aspect of time the number of years considered should ideally be from the time landfill came into operation, i.e. the age of a given landfill being assessed. As far as the past aspect of time for a given site is concerned, it may not be of as much significance from the point of view of overall risk assessment as such. For instance, if a landfill is 50 years old, it may not be necessary to consider how risky it was in the past when the landfill was only 10 years old. Therefore, the present and future aspects of the landfill will be important matters from the perspective of overall risk analysis. However, past aspect of time may still be necessary for risk analysis parameters as individuals if not for risk assessment overall. For instance, the history of the site, the types of wastes infilled in the past, quality of leachate, etc. Such information will be helpful to assess the present and future risks from the landfill. To assess the risks for present and future (Hallman and Wandersman, 1995), some parameters may have to be assumed not to vary for instance, the geological characteristics, but some may have to be accounted for such as fluctuation of groundwater in terms of mean groundwater level through the year. Thus there is an indefinite number of possible scenarios in this group alone, and the Risk Assessment Methodology developed in this project is left flexible for the risk assessor to account for such scenarios to the best of their knowledge and skills. It must be noted that it is individual risk assessment parameters which need to be looked into from past, present and future aspects of time in order to eventually constitute the overall risk analysis.

2.3.3 Space – Area and Depth

The term space is split into two sub dimensions, the Area and the Depth. The 'space' issue or spatial variations aspect is addressed for the pollutant source that is a given landfill, potential pathways and the potential targets / receptors as follows.

2.3.3.1 Landfill Site as a Point Source

Variations in items like wastes infilled and leachate qualities could be either along area or depth or both in a given landfill body. This variation is addressed with the philosophy of mean values, which can be based at the physical centre or effective centre of the considered volume of a given landfill site. This centre in the considered landfill volume could be seen as a point source. Determining maximum and minimum values of items, for instance, maximum COD value can also be useful to assist in estimating worst case and least bad risk scenarios (for more details see Sections 2.3.8 and 2.3.10 below, and Chapters 6 and 7). For that, sampling may have to be carried out at different points in the landfill body. However, the mean values can be helpful to estimate risk for mostly like scenarios. The temporal variation issue is already addressed in Section 2.3.2 above.

2.3.3.2 Pathway as a Line of Migration

A pathway along with its links (called media in this research study) also occupies space. For simplicity it can be seen as a line, that is no cross sectional area but length only. For instance, the migration of leachate hazards with groundwater movement can be seen along a line rather than along a space for simplicity. In other words, this can be treated as two-dimensional (i.e. 2D) approach. However, various physical, chemical and biological attenuations in the leachate as it migrates along a pathway can be taken care of by the LandSim model if being used as a migration assessment tool. Further details are provided in Chapter 6 regarding computer model development, where the 'Migration Assessment' module is discussed.

2.3.3.3 Target as a Point Receptor

Like a landfill site, a given target can also be considered as a point receptor / target. For instance, a human population or live stock (like fish farm) can be seen as a point receptor. Similarly groundwater may be seen as a point target where this point could be assumed in the centre of the area interfaced with the given landfill area, that is, the shortest and straight most path from the landfill to the groundwater. Even if pollutants in the leachate do not actually follow this shortest vertical path, but some other non-linear longer route, then this will add up on the degree of 'conservativeness' in terms of time to travel and attenuation.

2.3.4 Various Site Management Parameters

Site management comprises a very wide range of issues or items such as site history, waste types, waste management, site operations, site engineering. These parameters further branch out into various sub-items. For instance, site engineering includes liners and their types, capping and their types, leachate collection system, leachate treatment.

Thus, this group of scenarios alone contains an indefinite number of possible characteristics of landfills. Due to brevity all of such items and sub-items of site management are not addressed to full but to a limited extent in the Risk Assessment Methodology / Model.

2.3.5 Lithosphere, Atmosphere and Hydrosphere

A given landfill can be considered as surrounded by three main non-living factors of the environment, which are lithosphere, atmosphere and hydrosphere. Non scientific terms are soil / land, air and water, respectively. A given landfill, i.e. the pollutant source, exists in lithosphere and may physically be touching hydrosphere and atmosphere. However, potential pathways and targets exist in all of these factors of the environment.

In the scope of the project, atmosphere is not being considered as much as lithosphere and hydrosphere. The main reason is that the RAM covers leachate not gas. However, leachate may have a 'vaporisation into air' scenario to some extent and this aspect is particularly allowed for in the Exposure Assessment module of the Risk Assessment Methodology / Model in terms of inhalation exposure route (Chapters 4 and 5). Potential pathways and targets / receptors in the lithosphere, hydrosphere and atmosphere are considered in this research project. Moreover, hydrosphere and lithosphere are also covered in the Baseline Study section of the RAM mainly under geology, hydrology and hydro-geology modules. Further details on the development of the RAM and computer model are given in Chapters 5 and 6, respectively.

2.3.6 The Landfill Site and the Region

From a geographical point of view, the area under risk assessment consideration has been divided into two parts, which are the area of a given landfill site and that of the region which surrounds the given site. Almost all parts and sub-parts of the Risk Assessment Methodology / Model are common to a given site as well as the region surrounding it, for example, geology, hydrology, hydro-geology. So in this research project a given 'landfill site area' implies either the whole site area or the area of the site being assessed. The rest of the surrounding area stretching as far as, for instance, the catchment area (EC, 2000) or the farthest target, is referred to as the region. However, one reason for considering region around a given site is that most pathways exist in the region and so do the receptors / targets, though some of the receptors / targets may be on site as well, e.g. on-site workers, vandals.

2.3.7 Landfill Products

A landfill gives products in all three states that a matter may exist in, that is, solid (i.e. more or less degraded wastes as solid), leachate as liquid and landfill gas as a combination of different gases like carbon-dioxide, methane, hydrogen sulphide (DoE, 1991; Crowhurst and Manchester, 1993; Environment Agency, 2003c). This is illustrated in Figure 1.2. All these three waste products of a landfill are hazardous to the environment. In this research work only leachate is included in the scope while gas and degraded waste are excluded for further study by succeeding researchers.

2.3.8 Penta M – 5 M's

There are many parameters, particularly in the Baseline Study section, in the computer model of the RAM (discussed in Chapter 6), which can be measured or estimated with a range of mean, maximum and minimum values (Spence, 2000). For instance, consider the item 'precipitation'. Suppose there are more than one method applied to measure precipitation in the region in which a given landfill is situated. Each method yields a set of a maximum, a minimum and a mean value of precipitation. So there may be as many such sets as methods and / or sources of information like local meteorology centre. Moreover, if a single method (like Precipitation Gauge Method) is applied at different times and / or at different points in the region, for each set of time and / or place, there will be a set of maximum, minimum and mean values due to temporal and spatial variations for this one method alone. All such values from different methods as well as the same method applied more than once at different times and places can be stored in the computer model. The model is so designed that it will run a programme to bring up the highest and lowest maximum values out of all the maximum values of all the methods applied at different times at different places in the region. Similarly, the model will return the highest and lowest minimum values of precipitation and also work out average of all the mean values. This philosophy of highest Maximum, lowest Maximum, highest Minimum, lowest Minimum, and average of Means, has been referred to as Penta M or 5 M's in this study. The highest maximum value, average value of means, and lowest minimum value of precipitation can be useful in estimating worst case, most likely and least bad scenarios of landfill risks, respectively. This issue is further explained in Chapter 6. From the perspective of the scope of this research work, the 5 M's concept has been developed, introduced and applied to a number of parameters in the Baseline Study section of the RAM and computer model. However, due to brevity and the indefinite range of landfill scenarios, it was not possible to apply the 'Penta M' concept to all the parameters in the RAM. This approach will assist to carry out risk assessment along three themes, which are worst case, most likely and least bad risk scenarios. More details on these themes are provided in Section 2.3.10, and later in Chapters 5 and 6.

2.3.9 Methods of Measurement – Six Categories

As explained in Section 2.3.8 above, there can be more than just one method and / or sources of information to measure values of a parameter. Therefore in this study a concept of classification of measurement methods into six categories has been developed and introduced in the RAM and computer model (see details in Chapter 6). This concept has been applied to full scale to some parameters (like precipitation, interception, runoff), mostly in the Baseline Study section of the model. However, this concept has not been applied to all the parameters in the model due to brevity.

2.3.10 Worst Case and Most Likely Risk Scenarios

It is recommended that risk assessment should be covering most likely as well as worst case scenarios (Environment Agency, 1999; 2003a). However, a general trend of risk assessors and risk managers is that they adopt the most likely / mean scenarios (Craven, 2003). In the light of these facts, the RAM and computer model (See Chapters 5 and 6, respectively) are designed to allow for worst case, most likely / mean and least bad scenarios. On the basis of 'Penta M' concept, mentioned in Section 2.3.8 above, an example is used to explain these three risk scenarios as follows. The averaged out mean value of a parameter, for example Cadmium (Cd) concentration in a given landfill leachate, is useful in working out the most likely risk scenario. The maximum (highest) concentration of Cd in the leachate over time and space in the landfill body is worth considering from the perspective of worst case scenario. Whereas the minimum (lowest) Cd concentration in the leachate could be used to work out least bad scenario of risk. This would be even less likely than the most likely risk scenario. Therefore, the first two risk themes are more significant than third. However, still the least bad risk scenario along with worst case risk scenario helps in depicting the total range of risk with most likely risk generally sitting somewhere between the two extremes. Further details are laid down in Chapters 6 and 7.

2.3.11 Difference between Most Likely and Mean

Strictly from the perspective of the subject 'statistics', there is difference between the concepts 'most likely' and 'mean'. The former is based upon the value of a parameter, such as porosity, which repeats itself most frequently. On the other hand the latter is simply the average of all the occurrences or numbers (like average porosity). The two values, that is, one which is most frequently repeated and the other which is the average of all the values may or may not be the same or equal. In this research the model is developed such that it would take either the most likely value of a parameter or the mean depending which one a risk assessor decides to consider. This is further discussed in Chapter 6. However, it may be generally safe to assume at times that there will not be much discrepancy between most likely and mean values for a parameter. For instance, in the geology of a given landfill, the number of fractures or fissures per unit volume, if averaged out, would more or less be close to the most frequently repeated value. However, if a risk assessor still wishes and can manage to establish the most likely value of a parameter, the computer model can accept the most likely value instead of the mean value of the parameter. However, the model is not capable of considering both most likely and mean values in the same iteration.

2.3.12 Potential Targets / Receptors

There is a huge range of potential living and non-living targets / receptors. The project scope does not allow for all of them to be taken into account with full details. The targets which are the main focus of the project e.g. human beings, groundwater and surface waters, are covered in greater details comparatively. However, the study classifies all potential receptors / targets into comprehensive groups in Chapter 5.

2.3.13 Potential Pathways

There are numerous potential pathways and they all cannot be considered within the given scope of the research project. One of the main reasons is that the project is regarding landfill leachate only and not the other two products, i.e. landfill gas and degraded wastes (mentioned earlier in Chapter 1). Therefore, pathways in connection to landfill leachate are the prime concern in this study. Moreover, in the RAM and computer model a few of the general leachate-related pathways are taken into account with comparatively greater details than others. Examples are hazards migration via vertical unsaturated medium (if any), vertical saturated zone, horizontal movement / advection of the groundwater via aquifers. The exposure routes include inhalation, dermal contact and ingestion for living receptors like humans, and simple induction as far as non-living targets like groundwater and surface waters are concerned. However, pathways involving a river contaminated by leachate pollutants, leachate-contaminated land, etc. are not covered in detail due to brevity. See Chapter 5 for more details on how pathways are addressed in this research study.

2.3.14 Potential Hazards

There may be many potential hazards posed by landfill leachate, varying from one landfill scenario to another. To an extent some hazards are included as databases in the RAM computer model. The scope of the research does not allow for all the potential hazards of landfill leachate to be included in the databases. However, the model is flexible enough to consider any potential hazard that a risk assessor wants to assess.

2.3.15 Database Limitations

In addition to the databases indicated in Section 2.3.14 above, the RAM and computer model do not describe methods of measurement for various parameters such as groundwater ingress, liquid wastes. However, in the form of a database, some methods are contained in the model for a few parameters. Examples of these parameters are exposure quantification via exposure equations; leachate quantification via a number of empirical methods; pollutants from List 1 and List 2 substances from the Groundwater Directive. These can be seen as the modest databases of the model. It simply was not viable within the project scope to include all the methods of measurement for all the wide-ranging parameters involved in the RAM and model (see Chapter 5, Section 5.3).

2.3.16 The Baseline Study Section of the RAM

The Baseline Study section of the RAM and computer model consists of eight modules (See Chapters 5 and 6, respectively). One of these modules is hydrology, which has been covered in detail in the model. The remaining seven modules are not addressed to the same level of depth, both in terms of structure as well as parameters. For instance, in the geology and hydro-geology modules in the model, parameters like drift thickness, bed rock porosity, hydraulic gradient, water table, permeability are only listed. These can be expanded on by future researchers, by following the advice made in the hydrology module to render the Baseline Study section more comprehensive.

2.3.17 Waste Types and Landfill Size

The model presented in this study is independent of the types of wastes (hazardous or non-hazardous) that are buried in a given landfill and can take into account any pollutants. Therefore the model can accommodate any pollutant irrespective of whether they come directly from buried wastes, or as a result of any chemical, physical and / or bio-chemical waste degradation processes. The model does not consider unlimited scenarios of waste degradation, but the resultant pollutants only. The model is also independent of landfill size issue as the model is based on working out an effective centre point in the landfill body as a pollutant point source.

2.4 The Risk Assessment Methodology (RAM) and Computer Model

This study establishes knowledge gaps in risk analysis approaches to date by considering risk assessment as an entity. The study attempts to fill these gaps to various appropriate levels as per the scope of the research project. The project also investigates various constituting items or factors of risk analysis as individuals, thereby establishing knowledge deficiencies in them. These deficiencies are attempted to be bridged to suitable degrees. Due to the study of risk assessment as stand alone and its constituting blocks as individuals, this document is bound to have some repetitions.

Thus, the main purpose of the study is to draw all factors of risk assessments into one place and in the form of a more complete, sequential, and continuous format, which a user could follow from the start to the end for landfill leachate. Moreover, this project is not merely an integration of the factors in terms of just putting together under one umbrella of a risk assessment methodology. Rather it also includes a knowledge-base in the form of a corresponding computer model with allowances analysis (both internally and externally) as well as inter-connections between the factors for mutual information transfer. The RAM and computer model (Chapters 5 and 6, respectively) contain a logical and comprehensive categorisation of its parts into numerous sections and sub-sections in an algorithmic fashion. *However, it should be noted that the remit of this research work does not include addressing all the modules and sub-modules fully.*

2.5 The Research Methodology

The research methodology of the project should not be confused with the Risk Assessment Methodology (RAM) developed in the project. These are two separate and different issues. The former is what has been applied to conduct the project, where as the latter is an output or product of the project. The steps of the research methodology are listed as follows:

1. Reviewed literature on environmental risk assessments in general, followed by more specific literature to landfills.

2. Investigated computer models regarding environmental risk analysis in general and those specific to landfills.

3. Established knowledge gaps that exist currently in risk assessment approaches.

4. Identified limitations of existing computer models from the perspective a holistic risk analysis especially focusing landfills.

5. Prepared a list of all factors related to risk analysis of landfill leachate and gathered them under one umbrella.

6. Researched and adapted the non-integrated information on various risk assessment aspects in the literature. There were two purposes of the adaptation the information. Firstly, to transform the information into landfill leachate perspective, and secondly, to enable these pieces of information be assembled into a holistic methodology.

7. Researched and expanded upon the state-of-the-art of the relevant literature on a range of risk assessment facets to close knowledge gaps in landfill leachate context.

8. These steps made it possible to design a holistic framework encapsulating wide-ranging modules and sub-modules of the Risk Assessment Methodology (RAM) presented in Chapter 5.

9. The framework assisted in mapping out relationships between modules and sub-modules of the RAM.

10. After considering a number of master computer programmes and consulting computer programming experts, MS Access with Visual Basic Applications (VBA) embedded in it was selected for a computer model development.

11. The RAM was then translated into an electronic presentation in the shape of a knowledge-base computer model using the above computer programme.

12. Developed links in the model for making it possible for the user to systematically manoeuvre to different sections of the model easily and promptly.

13. These links were also established in order to add the feature of mutual information transport between various model constituents.

14. Some databases were also stored in the model to be used by the landfill assessor when appropriate.

15. Tested the computation and functionality of individual items of the model with synthetic data.

16. Validated the RAM computer model with a real landfill site data.

17. Recommended further research potentials for the future.

<u>Note:</u>

It is worth mentioning at this point that the nature of this research work is such that it cuts across a substantially wide variety of science disciplines and their various and numerous aspects. These subjects include toxicology, epidemiology, statistics, health physics, geology, hydrology, hydro-geology, topography, geography, environmental studies / sciences, biology, chemistry, ecology, sustainable development philosophy, environmental management, waste management, environmental legislation, information technology, computer programming and even computer modelling. Just one of the above subjects, that is hydrology, is picked to give a flavour of what is implied by the terms 'aspects' as follows. Aspects of the subject hydrology comprise, for instance, precipitation, evapo-transpiration, interception loss, percolation, infiltration, surface runoff and sub-surface watercourses. And the case is identical with the other disciplines in terms of their facets involved in this project. Whilst the aforesaid complex network, the focal point of the research has been environmental risk assessment in the context of landfill leachate. It has been a challenge to determine all relevant areas of these wide-ranging subjects to varying appropriate degrees to put them all together into perspective of landfill risk analysis. Due to this unusual nature of the project the reader will find quite a few cross-references in this document. Moreover, it has been a constant grappling task in terms of establishing compromise between 'breadth' and 'depth' of these subjects and their aspects such that the functionality of the RAM computer model (discussed in later chapters) is achieved to a reasonably demonstrable extent.

Chapter 3

THE REVIEW OF LITERATURE ON RISK ASSESSMENTS

This chapter states that risk analysis is not only increasingly being applied to environmental issues but to a range of other business fields. The chapter particularly critiques literature on environmental risk assessments from the perspective of landfills. It highlights knowledge gaps that exist in the literature to date in relation to risk analysis methodologies of landfills, thereby establishing that a strategic risk analysis methodology for landfill leachate does not exist. Furthermore, this chapter does not only critique risk assessment overall but also hazard assessment as an individual entity in itself, whose quantitative output is required at the heart of risk estimation and assessment. Also, the chapter deals with the risk analysis factors (including baseline study, hazard identification and categorisation, exposure assessment, and hazard concentration assessment) individually, to further reveal how developed these individual constituents of risk assessment are. The literature review is predominantly presented in the format of tables and there is bound be some repetition when the same literature is considered not only for hazard assessment and risk analysis but also for the individual constituents.

3.1 Risk Assessment (RA)

Risk analysis process can assist in drawing cost-effective compromises between economic and environmental costs thereby assuring that the philosophy of 'sustainable development' is adhered to. Risk assessment is a new research area relatively and in-growth science (Butt and Oduyemi; 2003). This is not just in relation to landfills and other environmental issues but also regarding wide-ranging fields such as food industry, ecology, epidemiology, health physics, immunotoxicology, radiation, earthquakes, finance, construction management, building contract selection, insurance, economics, project management, oil industry, business, regulatory systems, clinical governance, hospitals, government departments, flood risks, and IPC (Integrated Pollution Control) Processes (IoD, 2003; Brebbia, 2000; Scot and Stone, 2004; CIWEM, 1999; DETR et. al., 2000; Carter and Smith, 2001; Thomas, 1998; Mitchell, 1998; WHO, 1992; 1996; 1997; Rejda, 1995; HSE, 1996a; 1998; 2003; EPA, 1992; CHEM Unit, 2003; Chicken, 1994; Kwakye, 1997; Flanagan and Norman, 1993; Riggs and West, 1986; Mawdesley, 1997; Godfrey, 1996; Raftery, 1994; Hayes, 1987; Taylor, 1993; Marshall, 1994; Poynter-Brown, 1995; Lardi, 1993; Selcuk and Yucemen, 1998; Environment Agency, 1997b; ODPM, 2001; 2005; 2006; Crowther, 2004). However, in this study, literature on risk analysis that is related to environmental issues and specifically regarding landfills has been the main focus of the review. Some examples of such literature are listed below and more are discussed in Table 2.1, which assist in determining the state-of-the-art of risk analysis, identify knowledge gaps and eventually, via bridging these gaps, develop an overall framework of risk assessment. Moreover, professionals in the field of environmental waste management were also approached to gather information directly from the industry. However, some old literature was also considered to ensure if any research was conducted previously to develop a holistic risk assessment methodology.

Smith et. al., 2003	Elliot et. al., 2001
Dever and Gregson, 2004	Chrostowski and O'Dette, 2002
Ali, 1999	Hoehn et. al., 2000
Dolk, et. al., 1998	Vrijheid et. al., 2002
McNamee and Dolk, 2001	Axelrad et. al., 2001
Harrold, 1999	DPI, 2003
Kwiatkowski, 1998	EHSC, 2001; 2004
Crandall et. al., 2001	DWAF, 1998a; 1998b; 1998c; 1998d
Whiting et. al., 2001	Cleek and Bunge, 1993
Fazil et. al., 2001	O'Connell, 2001
Petts et. al., 1997	Cooke, 1999
Fox, 1999	Blight and Fourie 1998
Pollard et. al., 1995	Flavin and Harris, 1991

Harris, et. al., 1984	Royal Society, 1996
Glover, 1999	Woolgar, 1999
Budd, 1984; 1986	Robinson, 1998
Robinson, 1999	Jardin and Pelmont, 1993
Shen, 1985	Aboujaoude, 1993
CIRIA publications (see reference list)	EPA publications (see reference list)
Moore, 1999	DEFRA publications (see reference list)
Environment Agency publications (see reference list)	Ministry for the Environment, 2001; 2003; 2004
Committee on Techniques for Assessing Ground Water Vulnerability, 1993	
HSE, 2004	Graf and Schmidt-Tranb, 2001
Kang et. al., 1999	Taravona et. al., 2000
Watt, 2002	SEPA, 2002a; 2003; 2005a; 2005b
SIMRAC, 2004	Bennett, 1998
Wilson, 2000	Palmer and Wiseman, 1999
Burger, 2002	Baxter et. al., 1999
Garant, 1995	ERL, 1990a; 1990b
Chapman and Wang, 2000	Bridges et. al., 2000
Sharma and Gamble, 2002	Elander, 2000
Resnikoff, 2001	Karl, 2003
Fred Lee and Jones-Lee, 2004a; 2004b	Tromans and Stiles, 2004
Marsland and Carey, 1999	BS5930, 1999; BS10175, 2001
Axelrad et. al., 2005	Friebel et. al., 2004

Regardless of the type of risk analysis and the environmental area of application, the basic theme or fundamentals are the same. That is, for a risk to exist there has to be a target / environmental receptor which may be affected by a hazard or unwanted event via a pathway. Other common elements are listed below. These are also briefly indicated in Table 3.1. However, definitions and details on these items are laid down in Chapter 5.

1. baseline study

2. hazard identification
3. hazard concentration assessment
4. exposure assessment with exposure quantification
5. uncertainty assessment
6. significance assessment
7. pollutant migration analysis
8. likelihood or probability of a receptor to be effectively hit by the hazard (including hazard indices, risk quantification / measurement)
9. risk measurement for most likely and worst case scenarios

The literature review led to the conclusion that a comprehensive, robust and sound risk assessment methodology in an integrated manner with features (examples below) does not exist for landfills in particular (Butt and Oduyemi, 2003):

- encompassing the various types of landfill systems and their surroundings;
- taking into account all possible characteristics of landfills in terms of risks and quantification of risks posed by landfills;
- embedding procedures for the relevant items or modules (listed 1 to 10 in Table 2.1) and their sub-modules; and
- encapsulating other features and scenarios (examples listed 11 to 16 in Table 2.1) that could render a risk analysis process more comprehensive.

A range of knowledge limitations has been found in the literature reviewed to date. One of the most common knowledge gaps has been that of a user-friendly, sequential / stage-by-stage, categorical, in detail and yet integrated and quantitative methodology for carrying out risk assessment in a holistic manner specifically for landfill leachate. Consequently, such a holistic procedure of risk analysis does not exist in the form of a computer model either; as to translate a methodology into a corresponding computational approach the former has to be developed first. The driving force behind this research study is to make possible the development of such a computer-aided RA model, which is comprehensive and yet only specific to landfill leachate. The problem is that the literature to date is limited, indirect and in a piece-meal manner. Brief remarks on the review of some of the literature and the characteristics of the knowledge gaps and limitations are contained in Table 3.1 below. *It should be noted that the term 'holistic' in this document implies an overall framework encompassing or encapsulating all aspects and factors of the risk assessment of landfill leachate from the start (baseline study) through a range of modules and sub-modules to the end where hazard indices are calculated and risks quantified.* This definition is elaborated further in Chapters 4 and 5.

Table 3.1: Literature Review Examples – Discussion on elements of landfill risk assessment (RA) present and absent (Butt et. al., 2008)

Publication	Elements Present	Elements Absent
Golder Associates, 2002	This publication regards risk assessment only for small and closed landfills. It briefly mentions hazards and risks in the context of contamination of groundwater; contamination of surface water; gas accumulation; and direct exposure to contaminated soil, sharp objects or hazardous gases. These are the only four scenarios, which this publication addresses very briefly.	The term 'elements absent' implies knowledge gaps and limitations of the research works carried out to date. 1. This publication is not attempting to present a total risk analysis (RA) methodology that contains the features and the modules with their sub-modules (listed below) integrated together in an algorithmic, ready-to-use, sequentially linked, categorical, user-friendly format, continual and step-by-step, which a user could holistically follow from the start to the end in a self-guiding fashion. The framework of such a holistic methodology is presented in Chapter 4. 2. A detailed baseline study system, which could

		assist a risk assessor to identify and categorise all landfill site characteristics that are needed in different stages of the risk assessment process, is not in the remit of this publication. Examples are: • Geology: top soil, drift, rock, porosity, effective porosity, fissures, density, geological materials and minerals, depth & width or volume of the geological materials, and other geological properties • Hydrology: evaporation, transpiration, interception, (surface) runoff, infiltration, percolation, groundwater ingress, etc. • Hydrogeology: vadose and phreatic or unsaturaded and saturated zones, perched groundwater, hydraulic gradient, permeability, groundwater speed & direction, and other hydro-

		geological properties. • Topography: landforms / inclinations (to assist in measuring runoff to or from a given landfill), natural environment, habitats, built environment, water-courses, etc. • Geography: latitudes, longitudes, geographic zones e.g. tropical and other geographic properties that can also help in estimating other baseline study parameters like expected rainfall. • Meteorology: precipitation (duration, frequency, intensity), wind speed & direction, wet & dry bulb temperatures, humidity, degree of sun and cloudiness, etc. • Human influences: past, present and / or future potential anthropogenic activities like quarrying, water abstractions, construction and

		development. • Site management: site history, site type, site location, site design & engineering (e.g. liners, drainage system), waste management activities, environmental monitoring, waste types. 3. It is not in the scope of this publication to develop a procedure for hazard identification and categorisation to assist a risk assessor to group hazards in categories such as toxic, non-toxic, carcinogenic, non-carcinogenic, hazards due to settings / layout and / or processes, leachate quantification, leachate qualities (like maturity, age, hardness), etc. 4. Does not offer approaches to categorise and establish concentration levels for various pollutants both temporally and spatially. For instance, concentration levels at a landfill (the

		pollutant source), exposure medium, receptor intake concentration, thresholds or safety levels, background or existing concentration in a given receptor before leachate reaches. 5. There is no strategic procedure to carry out exposure assessment process in a quantitative manner for landfill leachate, which could take account of all possible scenarios. There is lack of in-depth algorithmic exposure quantification system that sequentially ties together the factors involved such as exposure duration, frequency, exposure media and routes. 6. Significance assessment of all characteristics and parameters of the modules and sub-modules of the risk assessment. For instance, is the amount of interception and / or liquid waste for a given landfill significant enough to consider in leachate quantity measurement;

		what conservative measures are taken for what parameters and why; etc. 7. Uncertainty assessment of all characteristics and parameters of the modules and sub-modules of the risk assessment. Where these uncertainties could be due to models' limitations; estimation methods; data quality; etc. 8. Migration assessment of pollutants in the form of categorical and sequential procedure is not present. This should include features of both pollutants transport phenomena (such as dispersion, advection, retardation) and attenuation phenomena (like dilution, absorption, adsorption, cation exchange reactions). 9. No details on hazard indices specifically in the

		context of landfill leachate whereas hazard index is a very important quantitative indicator of risk levels and therefore a significant feature of quantitative risk assessment. 10. There is no strategic procedure of risk quantification / measurement in which a risk assessor could consider all leachate hazards via all possible pathways for all possible receptors in an integrated fashion to work out total risk as well as individual risks on the basis of one hazard via one pathway for one receptor. 11. There is no evidence of consideration given to work out worst case, most likely, and least bad risk scenarios. 12. A given landfill can be at pre-operation stage (i.e. design and development phase), in-operation stage and / or post-operation stage

		(i.e. completed and post closure phase). The issue of each of the three landfill stages, which a given landfill could be in, is not discussed. 13. For risk assessment to be quantitative, all relevant parameters of the modules and sub-modules need to be quantified. The more the objective measurement of such parameters the more successful quantification of the risk will be. The publication does not seem to be able to touch on quantitative aspects of various risk assessment parameters (e.g. interception, precipitation etc.) 14. There is lack of 'aggregation facility' in the modules and sub-modules of the risk assessment. For instance, if a living receptor like human receives pollutant via dermal contact as well as ingestion. So the total concentration entering the human's body

		would be the sum of the concentrations via these two individual exposure routes. 15. There seems to be lack of consideration of temporal and spatial variations of various parameters of risk analysis modules and sub-modules. For instance, temporal variation of leachate quality that is in terms of becoming mature over time or aging; spatial variation of unsaturated / vadose zone underneath a given landfill in order to figure out effective vadose thickness; etc. 16. Lack of employment of statistical descriptions particularly in the context of maximum, minimum and most likely values of various parameters (e.g. precipitation, concentration of pollutant reaching receptors, exposure duration). Such statistical descriptions can be helpful to figure out worst case and most like

		risk scenarios as well as address uncertainties and temporal and spatial variations. 17. The publication is not for large landfills. It is not for pre-operation and in-operation stages either.
Environment Agency, 2003a	Provides guideline for risk assessment of landfill leacahte. Hazards are considered from the perceptive of groundwater as a receptor / target. In the form of a flow chart diagram of risk assessment process, some elements such as hazard identification, risk estimation and critical / threshold concentrations are mentioned. Some modules of the BS such as geology and hydrogeology are also included.	In the literature review this publication appears to be closest to what this research study is attempting to achieve, that is develop a more strategic, sequential and integrated RA methodology for landfill leachate (Chapter 4) along with a corresponding computer model (Chapter 5). Apart from some aspects of some RA modules (as highlighted in the left column), overall all the elements from 1 to 16 above are either absent or not addressed to a degree where they all could be tied together into an algorithmic procedure of quantitative RA. Some elements are not in the scope of the document and examples are as follows. Exposure quantification aspect is not in the remit of the publication. Apart from surface and ground waters,

		environmental receptors like humans, eco-systems, aquatic and terrestrial flora and fauna are not the main focus. Categorisation of hazards into toxic, non toxic, carcinogenic and non-carcinogenic streams so that hazard indices and risks could be measured and aggregated separately along these four streams. There is lack of employment of statistical descriptions such as maximum, minimum and most-likely values of various quantifiable hazard assessment parameters in particular to assist in establishing most-likely and worst-case risk scenarios. Though most of the baseline study areas are indicated, but the baseline study has not been categorised into a structure of eight headings / modules as indicated above – element 2. In particular the modules meteorology and geography are not included in this publication.
CIRIA, 2001	This publication is only for closed landfill sites. Both hazards and risks together are divided into three types namely, physical, chemical / bio-chemical and physico-	In-operation and pre-operation landfills are excluded. The publication is not specifically for landfill leachate. Though some of the RA modules' aspects (mentioned in the left column) are taken into account to an extent

	chemical. Thus, does not differentiate between hazard and risk for the above categorisation. Some aspects of some risk analysis modules (such as hazard identification, concentration assessment, exposure analysis) are addressed to an extent.	but not to a level where they could be put together in the form of total categorical and sequential methodology of RA. In summary, some of the elements from 1 to 16 above are partly addressed but not all of them in an integrated manner.
Gregory et. al., 1999	This publication is for risk assessment of landfill gas only. Touches on a range of risk assessment modules such as gas generation, human exposure.	Landfill leachate is not included in this publication. Thus, the elements (1 to 16 above) are completely absent from landfill leachate perspective.
Redfearn et. al., 2000	This publication, which is a paper, is related to risk analysis for landfill gas. Regards modules such as exposure assessment, toxicity assessment and risk estimation.	All the elements from 1 to 16 above are absent in the context of landfill leachate.
DETR et. al., 2000	This document provides material, in general, for the development of functional risk assessment guidance to assist issues like contaminated land, waste management, major accident hazards (DEFRA, 2002). It torches light on a range of aspects of RA such as	This publication addresses a range of risk analysis issues in general (listed in the left column). However, the focus is not only specifically landfill leachate rather a host of environmental hazards. Therefore it is general to a great extent. Moreover, the document does not present the framework in the form of a ready-to-

	dealing with uncertainty, types of quantification, evaluation of significance of a risk. This guidance is like a 'useful starting point'. It is to serve as the 'first port of call' for many Environment Agency officers before they tackle the detail and the same is hoped for everyone interested in risk-based decision-making in Government. (DEFRA, 2002).	use procedure of risk assessment in which all risk analysis modules and sub-modules could be put together in a logical and functional sequence. Thus the framework presented in the document is not readily convertible in to a corresponding computer model of risk assessment of waste disposal sites that a user could follow throughout. For instance, in-depth baseline study in-housing the eight modules (indicated above in element 2) does not fall in the remit of this document. Conclusively, all the factors from 1 to 17 above are absent in the context of being strictly specific to landfill leachate. Whereas the research work presented in this study encompasses the development of such a total risk analysis system which puts together all modules and sub-modules related to risk analysis process of landfill leachate in a sequential order. Not only that but also would be readily convertible into a corresponding computer-aided model incorporating inter-relations between the modules and sub-modules to render mutual

		information transfer possible where appropriate.
Environment Agency, 2003d	This landfill risk assessment publication is from the perspective of issues including noise, odour, litter, birds, vermin, insects, and mud on road.	The publication is not about landfill leachate in the first place. The elements 1 to 16 are absent.
Harris, 1984; Asante-Duah, 1990; DOE, 1994a; Jones, 1997; EPA, 2003b; Google, 2006; and Arell and Folkes, 2004.	These publications are on Hazard Ranking System (HRS) employing a scoring mechanism, which is a semi-quantitative approach i.e. neither purely quantitative nor entirely qualitative (Pollard et. al., 1995; Robinson, 1999; Lloyd and Wilson, 2002; EPD, 2004; Chapman and Wellington, 2004). HRS is a principal mechanism that the EPA (US) uses to place uncontrolled waste sites on the National Priorities List (NPL). It is a numerically based screening system that uses information from initial, limited investigations – the preliminary assessment and site inspection – to assess the relative potential of sites to pose a threat to human	HRS does not offer a holistic risk assessment methodology whose results could be used as an input to risk reduction / control to complete the risk management process as shown in Figure 2.2, Chapter 2. One of the reasons is that the information collected to develop HRS scores is not sufficient to determine either the extent of contamination or the appropriate response for a particular site. Moreover, the approach is not quantitative as presented in Chapter 6 in the form of a computer model. Also, a range of elements from 1 to 16 mentioned above are absent in HRS specifically from the perspective of landfill leachate.

	health or the environment.	
Bernard et. al., 1996; 1997	These two papers (Part 1 and 2) are on hazard analysis of landfill leachate. They discuss leachates from 25 landfills in France as case studies with a number of methods of determining leachate toxicity and then comparing the physico-chemical characteristics of leachates.	The publications are not on RA procedure at all. So all the elements 1 to 16 above are absent. However, the techniques identified on measuring toxicity of landfill leachate can be useful in exposure assessment and hazard concentration assessment modules of RA for a given landfill. However, these papers still do not present procedures for exposure analysis and concentration assessment modules as parts of RA.
Bardos et. al., 2003a; 2003b; SCEG, 2003; Nathanail and Nathanail, 2003	These four articles draw on some aspects of hazard assessment and risk analysis from the perspective of contaminated land.	These are not specifically for landfills and all the elements from 1 to 16 above are absent from the perspective of landfill leachate.
Environment Agency, 2004	This document briefly addresses a broad and diverse range of facets of landfill risk analysis along social, technical, environmental, economic, legislative and managerial themes. Both landfill gas and leachate are addressed. The main scope of the guidance is limited to five areas of risk assessment, which are accidents and their consequences;	As the document states itself that there are five main areas, which constitute the main scope of the guidance (listed in the left column). Yet landfill leachate is not one of them, though is addressed to an extent. The guidance also mentions that it does not provide all the detail needed to conduct risk analysis for a landfill. However, the authors find this guidance as the second closest to what authors are attempting to achieve, that

	hydrogeology; landfill gas; particulate matter; and stability.	is develop a more holistic, quantitative and computational RA methodology specifically for landfill leachate (described in Chapters 4 and 5). Examples of the elements from (the Golder Associates, 2002 row) above needing more or less further work are: hazard indices, deriving risks for worst case & most likely scenarios, consideration of temporal and spatial variations, statistical descriptions. Some of the elements (from the Golder Associates, 2002 row) above are not in the scope of the document and examples are as follows. Exposure quantification aspect is absent. Some of the baseline study modules like meteorology, human influence and geography are not addressed.
Pollard, Simon et. al., 2000	This document provides technical guidance to Environment Agency staff and to applicants on the practical environmental risk assessment tools that can be used in the waste management licensing process to assist in the design and operation of site. However, it	Although, this document introduces the concept and stages of environmental risk assessment but does not offer a holistic risk assessment methodology specifically for landfill leachate. There are a number of risk analysis concepts on which it touches either partly or not at all. The examples of such items are exposure

	needs to be used alongside the DETR/EA Guidelines for environmental risk assessment and management (DETR, et. al., 2000).	assessment, hazard indices, hazard concentration assessment, migration assessment, etc. Also, the publication does not offer algorithmic categorisation of these concepts to perform categorical risk assessment in terms of, for instance, toxic, non-toxic, carcinogenic and non-carcinogenic.
EPD, 1997	This publication is a guideline for hazard analysis of landfill gas. It briefly covers various aspects of hazard and risk assessment such as hazard mitigation measures and source-pathway-target analysis approach.	The publication is not for landfill leachate. Even for landfill gas the elements from 1 to 16 are either completely absent or very few are partly covered to limited extent (as mentioned in the left column). From leachate point of view, all 1 to 16 are totally absent.
ICRP, 1975; ICRCL, 1987; Eisenbeis, et. al., 1986; OSHA, 1989; Johannsen, 1990; Montague, 1991; Kavazanjian et. al., 1995; Jaggy, 1996; Asante-Duah, 1996; WDA, 1994; Pieper et. al., 1997; Senior, 1995; DoE, 1986; 1991; 1993; 1995a;	Some old literature (examples given in the left column) regarding landfill assessment in particular and other risk assessments in general, was also studied to make sure if there were any works done on RA in the longer past in terms of developing a holistic RA methodology. The literature have been found to address various risk assessment issues like seismic hazard analysis for landfills;	Element 1 above is totally absent where as the other elements are described to various levels in a piece-meal fashion (as indicated in the left column) and thus these publications do not offer a categorical and sequential procedure for RA in a holistic manner for landfill leachate which could readily be converted into a computer model as presented in Chapter 6.

CIRIA, 1993; 1995	carcinogenic and non-carcinogenic risks; air contamination; landfills' leakage; exposure assessment; baseline study; toxicity assessment; risk estimation; specific landfill type and nature; radiation; contaminated land remediation; specific hazards such as polychlorinated dibenzo-p-dioxins and furans (PCDD/F); landfill microbiology; landfill gas; landfill completion; landfill design and construction aspects.	
SEPA, 2002b	This publication regards landfill risk assessment in the context of landfill leachate liners and drainage systems.	Apart from the aspect of liners and drainage systems, which form part of site management sub-module of the baseline study above, the elements 1 to 16 are absent.
CPPD, 2004	Currently the publication is in a draft form. It regards hazard and risk assessment in the context of natural hazards such as flooding, earthquake, landslides, wildfire.	The publication is not for anthropogenic activities in the first place. Therefore does not consider landfills at all. Though discusses various natural hazards with statistics but does not present a structured RA procedure. The elements from 1 to 16 above are absent.
Rudland et. al., 2001	Describes a basic framework for the risk	Not for landfills in specific. All the elements from 1 to

	assessment of contaminated land.	16 above are absent in the context of landfill leachate.
Auckland Regional Council, 2002	This publication, which is a government document for local authorities, covers RA in a very broad sense of hazards. These include natural hazards such as tornado, flooding, earthquake; technological hazards like high pressure gas mains, computer systems failure; biological hazards including disease amongst people, animals or plants; and civil / political hazards comprising terrorism and civil unrest.	The publication is not specifically for landfills. It just encapsulates all natural and anthropogenic hazards without presenting a holistic RA procedure. The format is more like a checklist. In nutshell all the elements from 1 to 16 (above) are absent not only for landfills but any hazards in general.
Scott Wilson (Hong Kong) Ltd, 1997	The focus is landfill gas and also that of a specific landfill.	Does not offer a risk analysis methodology comprising 1 to 16 features above for landfill leachate and not even landfill gas.
Environment Agency, 1997c	This document addresses risk assessment from the perspective of only human health as receptor and only those landfills as pollutant source which contain house hold waste.	Does not present a risk analysis methodology encompassing 1 to 16 aspects above for landfill leachate in any shape or form.
DOE, 1998	This environmental guidance mentions Risk-Based Corrective Action (RBCA) standards developed for addressing petroleum and	The purpose of this document is not to present a strategic and integrated framework of risk analysis, and not for landfill leachate at all. The system

	chemical releases. The purpose of this guide is to explain risk-based decision making and the RBCA process for environmental restoration of chemically contaminated sites.	emphasises more on determining the data required for technical decision making rather than on following specific steps of a risk assessment process. All the elements 1 to 16 are absent from landfill lechate perspective.
EPA, 1998a; 1996a; 1996b; 1996c; 1988a	These four documents are regarding risk assessments of neurotoxicity, reproductive toxicity, ecology and carcinogens, respectively. The fifth publication is on evaluation of potential of carcinogenicity of Acrylonitrile.	Though these documents may indirectly be useful in risk analysis of landfill leachate in the context of establishing neurotoxicity, reproductive toxicity, ecological and carcinogenic affects of leachate pollutants. However, these publications are not produced specifically from the point of view of landfill leachate and thus in this sense all the elements indicated above are missing.
CMSA, 2004; Puncochar, 2003; Koivisto et. al., 2001; Feldman and White, 1996; CHEM Unit, 2003; Pauluhn, 1999; PDC, 2003; Thatcher, 2002; EPA, 2002a; Fred Lee and Jones-Lee, 2004a; Hull et. al. 2002; HCPC, 2004;	These publications are regarding hazard and risk assessments in the context of these respective subjects: mining, workplace, genetically modified organisms, neurology, indoor environment, ecology, toxicology, software, wildlife, terrorism and safety, human health and epidemiology, aquatic chemistry and aquatic toxicology,	These publications are not for landfills in the first place. All the elements listed above from 1 to 16 are absent from the landfill leachate perspective.

Catlin et. al., 2001; Hoffman et. al., 2003; Kinsman and Maddison, 2001; Hekster and Voogt, 2002; DOE, 1993; 1994b; Brown 2000; Norton, 2002; QUT, 2004; Keith et. al., 1999; Taravona, et. al., 2000; Fleming and Fleming, 2002; A-NPDC, 2004; Anderson and Albert, 1999; Jones et. al., 2004; Karvonen, 2000; Brown and Stringer, 2002; Ochola, 2002; DEM, 2004; Sanchez and Burger, 1998; UCL, 2002; Gillanders, 2003; Crawford-Brown and Brown, 1997; Chen et. al., 1998; Pease, 1992; Muth et. al., 2001; Tarazona and Vega, 2002; EPA, 2000a; and McKenna, 1998	seismology, natural hazards (like drought, wildfire / forest fire, storm, etc.), explosion, ecotoxicology, fires in agrochemical warehouses, aquatic environment, human health, contaminated land, food safety, health and safety, radiation, terrestrial environment, energy and electricity, shore environment, air quality, cattle import, economy, microbiology, farming machines, nuclear production sites, educational establishments, project management, carcinogenicity, petroleum contamination, regulations development, food, chemicals and eco-systems, chemical mixtures, and hormesis.	

3.2 Hazard Assessment

The review of the literature shows that hazard assessment (HA) provides a foundation for an environmental risk assessment process. The better and stronger this foundation, the more effective and efficient the risk analysis (RA) and the subsequent risk management (RM). This explains the significance of the HA. In a risk assessment process before the consideration of likelihood / probability of hazards hitting a receptor and consequent consequences; the identification, categorisation and analysis of all potential hazards, pathways, receptors and exposures have to be carried out (CIRIA, 2001; EQE International, 2004). The former set of constituents is referred to as risk estimation (R Esti) and the latter set of factors contribute the HA. For relationships between, HA, R Esti, RA and RM, see Chapter 2. Due to the significance of HA alone as established above, this research study also reviews more or less the same literature to investigate current HA status as an entity in itself. This investigation is contained in Table 3.2. With reference to Section 3.1 above, HA being part of RA, a part of the driving force behind this research project is to make possible the development of such a stand alone computer-aided HA model, which is quantitative and comprehensive, and yet only specific to landfill leachate.

Table 3.2: Literature Review Examples – Discussion on elements of landfill hazard assessment (HA) present and absent (Butt et. al., in press – a)

Publication	Elements Present	Elements Absent
Golder Associates, 2002	This publication regards risk assessment only for small and closed landfills. It briefly mentions hazards and risks in the context of contamination of groundwater; contamination of surface water; gas accumulation; and direct exposure to contaminated soil, sharp objects or hazardous gases. These are the few scenarios, which this publication addresses very briefly.	A range of elements are absent including the following: 1. Hazard assessment procedure is not described in a ready-to-use and user-friendly format, which a user could holistically follow from the start to end in a self-guiding fashion. There is lack of integration of various parts and sub-parts as well as a number of features elaborated below. 2. There is absence of baseline study aspect covering all the eight modules, which are geology, hydrology, hydrogeology, meteorology, geography, topography, site engineering, and human influence. Details in Chapters 5. 3. The identification and categorisation of leachate in these main groups namely, leachate quantity hazard, leachate quality hazards, process and / or layout hazards, and harms. Similarly, there is no further identification and categorisation for leachate quality hazards into the following groups: pollutant or property; toxic, non-toxic or both; and carcinogenic, non-carcinogenic or both. More details in

		Chapter 5. 4. There is lack of the identification and categorisation of pollutants at source (that is a given landfill), pathways (including exposure medium and exposure routes) and receptors / targets are absent. Also there is found no systematic procedure for measuring or quantifying exposure of receptors to hazards, covering all possible exposure routes via which hazards possibly can enter a given receptor boundaries such as ingestion, dermal, inhalation. There is no feature or facility of adding up the individual exposures from these exposure routes in order to work out total exposure to a given receptor / target from a given hazard. Further discussions in Chapter 5. 5. There is no categorisation system of hazard concentrations in these four groups: pollutants' concentrations at source (i.e. landfill), pathway and receptor / target; and critical hazard concentrations. Furthermore, the Initial (or background), Reaching and Final concentrations for both exposure medium and receptor / target, are absent. However, in case of a given receptor / target the term Reaching concentration is called Intake concentration. More details in Chapter 5. 6. There is no presentation of a holistic HA in this publication in the

		first place therefore there is lack of mutual inter-connections / relationships between various modules and sub-modules of the HA process. So the publication can not and does not clearly identify that which output of which module or sub-module will be an input to another module or sub-module. 7. This publication does not take account of all landfill sizes, types and systems. Also it does not regard landfills in operation or in planning stage. In other words this publication is not independent of landfill size and stages / phases which are pre-operation (i.e. design and planning stage), in-operation and post-operation (i.e. closed and completed stage). 8. There is lack of quantification features that assist in drawing quantitative results from the HA process of a given landfill in order to be used in the quantitative risk analysis. Details on such quantification features are described in Chapter 5. 9. Statistical descriptions of elements that can be measured numerically are not in the scope of this publication.
Environment Agency, 2003a	Provides guideline for landfill risk assessment of landfill leachate. Hazards are considered mainly from the perceptive of	This publication has not been prepared with the idea of developing such an integrated and stand-alone HA system, which could not only be used separately but also render a foundation in the form of quantitative results

	groundwater as a receptor / target. In the form of a flow chart diagram of risk assessment process, some elements such as hazard identification, risk estimation and critical / threshold concentrations are mentioned. Some sub-modules of the BS such as geology and hydrogeology are also included.	(explained in Chapters 5 and 6) that could be used as an input to the risk estimation stage to complete the process of quantitative risk analysis more holistically. In other words, although this publication is the closest to what this research study is attempting to achieve, which is to develop not only an even more strategic HA procedure (described in Chapter 5), but also such a HA framework which is readily and algorithmically convertible into a corresponding computer model (presented in Chapter 6) that would assist produce hazard indices for various landfill scenarios. This publication is not readily transferable into such a computer model where such hazard indices could be generated for all possible scenarios is not in the scope of this document. Some examples of items not included in the remit of this publication are listed as follows. Exposure quantification aspect is not in the scope of the publication. Apart from surface and ground waters, environmental receptors like humans, eco-systems, aquatic and terrestrial flora and fauna are not the main focus. Categorisation of hazards into toxic, non toxic, carcinogenic and non-carcinogenic streams so that hazard indices and risks could be measured and aggregated separately along these four streams. Employment of statistical descriptions such as maximum, minimum and most-likely values of various quantifiable HA parameters in particular to assist in

		establishing most-likely and worst-case risk scenarios. Though most of the baseline study areas are indicated, but the baseline study has not been categorised into a structure of eight headings / modules as indicated above in Point 2 o this table and Table 3.1, and further details given in Chapter 5. Baseline study modules on meteorology and geography are not particularly in the remit of this publication. Further details on these examples are described in Chapters 5 and 6.
CIRIA, 2001	This publication is only for closed landfill sites. Both hazards and risks together are divided into three types namely, physical, chemical / bio-chemical and physico-chemical. Thus, does not differentiate between hazard and risk for these three categories. Some aspects of some HA modules (such as hazard identification, exposure assessment, hazard concentration assessment) are addressed to an extent.	In-operation and pre-operation landfills are excluded. The publication is not specifically for landfill leachate. Though some of the HA modules' aspects (mentioned in the adjacent cell of the table) are taken into account to an extent but not to a level where they could be put together in the form of categorical and sequential HA framework (Details in Chapter 5). In summary, the factors from 1 to 8 above are partly covered to different limited degrees and yet not in a holistic format specifically for landfill leachate. Factor 9 has not been addressed.
Environment Agency, 2004	This document briefly addresses a broad and diverse range of facets of landfill risk analysis along the social, technical,	The guidance mentions that it does not provide all the detail needed to conduct risk analysis for a landfill. As the document states itself that there are five main areas, which constitute the main scope of the

	environmental, economic, legislative and managerial themes. Both landfill gas and leachate are addressed. The main scope of the guidance is limited to five areas of risk assessment, which are accidents and their consequences; hydrogeology; landfill gas; particulate matter; and stability.	guidance (listed in the left column). Yet landfill leachate is not one of them, though is addressed to an extent. However, the authors find this guidance as the second closest to what authors are attempting to achieve, that is develop a more strategic HA framework, which is presented in Chapter 5. However, the remit of this publication has not been to prepare such an integrated HA procedure as a separate entity in itself, which could render foundation and quantitative results in order to be used as input to risk estimation to complete the process of quantitative risk analysis more holistically. Some examples are listed as follows. Exposure quantification aspect is absent. Some of the Baseline study modules like meteorology, human influence and geography are not addressed. Further details on these examples are given in Chapter 5.
DETR et. al., 2000	The document provides material, in general, for the development of risk analysis guidance to assist issues like contaminated land, waste management, and major accident hazards.	The publication addresses a range of issues in general (listed in the left column). However, the focus is not solely landfills or landfill leachate, rather a host of environmental hazards. Therefore it is generic to great scale. The scope of this publication is not to develop an integrated standalone HA framework that could also assist quantitative risk analysis. For instance, in-depth baseline study in-housing the eight modules does not fall in the remit of this document. Conclusively, all the factors from 1 to 9 above are absent in the context of only specific to

		landfill leachate.
Gregory et. al., 1999	This publication is for risk assessment of landfill gas only. Touches on a range of risk analysis modules such as gas generation, human exposure.	Landfill leachate is not included in this publication. So the factors 1 to 9 (above) are absent from landfill leachate perspective.
Redfearn, et. al., 2000	This publication, which is a paper, is related to risk analysis for landfill gas. Regards modules such as exposure assessment, toxicity assessment and risk estimation.	All the factors from 1 to 9 above are absent in the context of landfill leachate.
Bernard et. al., 1996; 1997	These two papers (Parts 1 and 2) are on hazard analysis of landfill leachate. They discuss leachates from 25 landfills in France as case studies with a number of methods of determining leachate toxicity and then comparing the physico-chemical characteristics of leachates.	The publications are not on HA at all. So all the factors 1 to 9 above are absent. However, the techniques identified on measuring toxicity of landfill leachate can be useful in exposure assessment and hazard concentration assessment modules of HA for a given landfill leachate. However, these papers still do not present procedures holistically for these two modules as part of HA.
EPD, 1997	This publication is a guideline for hazard analysis of landfill gas. It covers various aspects of the subject such as hazard mitigation measures and source-pathway-	The publication is not for landfill leachate. Even for landfill gas the factors from 1 to 9 are either completely absent or partly covered to a limited extent (as mentioned in the adjacent cell of the table). From leachate point of view, all factors 1 to 9 are totally absent.

	target analysis approach.	
Bardos et. al., 2003a; 2003b	These two articles touch on some aspects of hazard and risk analysis from the perspective of contaminated land.	Although landfill is kind of contaminated land, these two publications are not specifically for landfills and all the factors from 1 to 9 above are absent from the perspective of landfill leachate.
Kavazanjian et. al., 1995; Eisenbeis, et. al., 1986; Jaggy, 1996; Asante-Duah, 1996; and Pieper et. al., 1997	Some old literature (examples given in the left column) on landfill assessment was also studied to make sure if there was any work done on HA in the long past. They covered various risk analysis issues like seismic hazard analysis for landfills, exposure assessment, baseline study, toxicity assessment, risk estimation, specific landfill type and nature, specific hazards such as polychlorinated dibenzo-p-dioxins and furans (PCDD/F).	Factor 1 is totally absent where as all the other factors addressed to various levels in a piece-meal fashion (as in indicated in the adjacent cell of the table) and thus these publications do not offer a categorical and sequential HA procedure in an integrated fashion for landfill leachate.
SEPA, 2002b	This publication regards landfill risk assessment in the context of landfill leachate liners and drainage systems.	Apart from the aspect of liners and drainage systems, which form part of site management module of the baseline study, the factors 1 to 9 (above) are absent.
Environment Agency,	This landfill risk assessment publication is from the perspective of issues including	The publication is not about landfill leachate in the first place. The factors 1 to 9 are absent.

2003d	noise; odour; litter; birds; vermin and insects; and mud on road.	
Rudland et. al., 2001	Describes a basic framework for the risk assessment of contaminated land.	Although a landfill is a kind of contaminated land, this publication is not for landfills in specific. All the factors from 1 to 9 above are absent from landfill leachate perspective.
Auckland Regional Council, 2002	This publication, which is a government document for local authorities, has a special chapter on H Iden but in a broad sense of hazards. These include natural hazards such as tornado, flooding, earthquake; technological hazards like high pressure gas mains, computer systems failure; biological hazards including disease amongst people, animals or plants; and civil / political hazards comprising terrorism and civil unrest.	The publication just encapsulates all natural and anthropogenic hazards without presenting a holistic HA framework. In nutshell all the factor from 1 to 9 (above) are absent not only for landfills but any hazards in general.

3.3 Baseline Study

The position of the baseline study aspect in various literature has been briefly indicated in the above two tables from the angle of risk analysis and hazard assessment, respectively. In this section some examples from literature are mentioned with the main focus on baseline study alone. A strategic procedure for carrying out baseline study for landfill leachate is one of the knowledge gaps, which exist in the literature. For instance, ICE (1994) describes risk assessment from the contaminated land point of view rather than from a landfill perspective. Furthermore, although this publication outlines the main contents of baseline study for assessing risks of any types of contaminated land, it does not describe a robust and objective procedure for carrying out baseline study even for contaminated land. Similarly, Asante-Duah (1996) describes various important aspects of risk assessment and risk management (including baseline study) but not in the form of a methodology rather independent of each other in different chapters. Moreover, like ICE (1994), this publication is also from the contaminated land perspective rather than specific to landfills, thus does it not cover a range of landfill aspects including leachate formation, migration and attenuation. Blight and Fourie (1998), although focusing on landfills only, still very briefly outline requirements of baseline study for landfill risk assessment. Environment Agency documents (1997a; 1999; 2003a) are more focused on landfills in risk assessment terms than other literature and outline clearly what should be the main contents of the baseline study. However, there is no description given on the procedure for carrying out the baseline study process.

In summary, in the reported literature to date no evidence has been found on how to perform a baseline study for risk assessment of landfills. The current practices for baseline study, particularly in the UK, have no organised approach to carrying it out since a strategic procedure does not exist in the first place. Different risk assessors carry out baseline study in different ways, depending upon a number of factors including the characteristics of a given landfill scenario, which also includes the degree of availability of the information. There is no system as such for all parts and sub-parts of the baseline study against which they can streamline a preliminary investigation process to provide foundation for the risk assessment of a given landfill leachate (Butt and Oduyemi, 2000).

3.4 Hazard Identification and Categorisation (H Iden)

The situation of the H Iden factor in various literature has been briefly highlighted in above two tables from the perspective of risk analysis and hazard assessment, respectively. However, this section solely emphasises on H Iden to establish its status in the literature in more detail. Brief remarks on the review of some of the literature and the characteristics of the deficiencies are contained in Table 3.3. It can be safely concluded from the table that the literature on H Iden to date is limited. The development of an integrated procedure for conducting hazard identification and categorisation (H Iden) specifically for landfill leachate appears to be a common knowledge gap. There has not been found an evidence of H Iden procedure accompanied with a corresponding computer model that integrates the seven elements indicated in the first row of Table 3.3. (Butt et. al., 2006a).

Table 3.3: Literature Review Examples – Discussion on elements of H Iden present and absent (Butt et. al., 2006a)

Publication	Elements Present	Elements Absent
Golder Associates, 2002	This publication regards risk assessment only for small and closed landfills. It briefly mentions hazards in the context of contamination of groundwater; contamination of surface water; gas accumulation; and direct exposure to contaminated soil, sharp objects or hazardous gases.	The term 'elements absent' implies knowledge gaps and limitations in research works to date regarding H Iden approaches from the perspective of landfill risk analysis. 1. It is not in the remit of this publication to describe a H Iden procedure in a ready-to-use and user-friendly format, which a landfill assessor could holistically follow from the start to end in a self-guiding fashion. 2. There is no computational format of the H Iden procedure, which a user could readily apply in combination with other modules and sub-modules of a total risk assessment process. 3. Identification and categorisation of leachate hazards is not divided into these main groups: leachate quantity hazard, leachate quality hazards, process and / or layout hazards, and harms (Details in Chapter 5).

		4. Further identification and categorisation of leachate quality hazards into the following groups is absent: Pollutant or Property; Toxic, Non-toxic or Both; and Carcinogenic, Non-carcinogenic or Both (Details in Chapter 5). 5. Classification of measurement methods of various parameters (such as leachate quantity estimation) into appropriate groups is not employed. Details on this aspect are given in Chapter 5. 6. This publication does not include the significance assessment feature. It also does not account for analysis of likely uncertainties in, for instance, methods of measurement of parameters such as precipitation and evaporation in leachate quantification. Links are provided for both the significance assessment and uncertainty assessment in the H Iden module of the RA computer model designed and presented in Chapter 6. 7. The statistical concepts of maximum, mean (or most likely) and minimum values are not in the scope of this publication. These three conceptual elements are

		embedded in the H Iden module of the RA computer model and illustrated in Chapter 6. 8. The publication excludes big landfills. Also it does not regard landfills in operation or in planning stage. Where as the H Iden system presented in Chapters 5 and 6 is independent of landfill size and phases. These phases or stages are three in number, which are pre-operation (i.e. design & planning), in-operation and post-operation (i.e. completed and closed).
DETR et. al., 2000	This document states itself that it provides material, in general, for the development of risk analysis guidance to assist issues like contaminated land, waste management, major accident hazards.	The document addresses a range of issues in general (listed in the left column) but not specifically for landfills or landfill leachate. The objective of this document is not to develop an integrated H Iden framework to assist quantitative risk analysis. In summary, in the context of landfill leachate all the five elements 1 to 7 above are not in the remit of this publication.
Environment Agency, 2004	This document briefly addresses a broad and diverse range of facets of landfill risk analysis along social, technical, environmental, economic, legislative and managerial themes. Both landfill gas and leachate are	A strategic H Iden procedure accompanied with a corresponding computer model is not in the remit of this publication. Statistical descriptions like maximum, mean and minimum leachate quantities are not in the scope either. As

	addressed. The main scope of the guidance is limited to five areas of risk analysis, which are accidents and their consequences; hydrogeology; landfill gas; particulate matter; and stability.	the document states itself that there are five main areas, which constitute the main remit of the guidance (listed in the left column). Yet landfill leachate is not one of them though is addressed to an extent. The guidance also mentions that it does not provide all the detail needed to conduct risk analysis for a landfill and the same is the case for the H Iden.
Environment Agency, 2003a	This document provides guideline for landfill risk assessment. Hazards are considered only from the perceptive of groundwater as a receptor. Hazard identification is mentioned as an initial stage in the form of a flow chart diagram of risk analysis process.	Though this publication regards risk assessment for landfill leachate but all the elements of H Iden from 1 to 7 above are absent. The implications of the LandSim software suggested by the document is discussed in Chapter 4.
CIRIA, 2001	This publication is only for closed landfill sites. Both hazards and risks together are divided into three types namely, physical, chemical / bio-chemical and physico-chemical. Thus, there is no differentiation between hazard and risk for the above categorisation.	In-operation and pre-operation landfills are excluded. The publication is not specifically for landfill leachate. All the points above from 1 to 7 are absent as well.
Gregory et. al., 1999	This document is for risk analysis of landfill gas only. Touches on a ranges of risk assessment modules such as gas generation, human exposure, pollutants migration, and yet not H Iden.	Landfill leachate is not included in this publication. Also the elements 1 to 7 (above) are absent.

Redfearn, et. al., 2000	This is a paper related to risk assessment of landfill gas and covers aspects such as exposure assessment, toxicity assessment.	No consideration given to H Iden procedure in the first place. Thus, in the context of H Iden, all the first seven elements above are not addressed at all. This publication is not aimed at landfill leachate.
Eduljee, 1998	This published paper is regarding risk analysis of household waste disposal sites. It very briefly describes hazard identification as an important module of risk analysis exercise.	All the elements from 1 to 7 above are absent.
Eisenbeis et. al., 1986; Jaggy, 1996; and Asante-Duah, 1996	Some old literature (examples given in the left column) on landfill risk assessment was also studied to assure if research works were carried out on H Iden comparatively in the long past. These old publications covered various risk analysis factors (like exposure assessment, baseline study, and risk estimation) but not H Iden procedure.	All the elements from 1 to 7 above are absent.
SEPA, 2002b	This publication regards landfill risk analysis in the context of landfill leachate liners and drainage systems. It does not present any H Iden procedure.	The elements 1 to 7 (above) are absent.
Environment Agency, 2003d	This publication on landfill risk analysis is from the perspective of issues including noise; odour; litter;	The publication is not about landfill leachate. The elements 1 to 7 are absent.

	birds; vermin and insects; and mud on road.	
CPPD, 2004	Currently the document is in a draft form. Its title is 'Hazard identification and risk assessment'. It addresses natural hazards such as flooding, earthquake, landslides, and wildfire.	The document is not for anthropogenic activities. Therefore it does not consider landfills. Though discusses various natural hazards with statistics but does not present a structured procedure for H Iden. The elements from 1 to 7 above are absent.
Rudland; Lancefield; and Mayell, 2001	This describes a basic framework for the risk assessment of contaminated land.	Not for landfills in specific. All the elements from 1 to 7 above are absent.
Auckland Regional Council, 2002	This is a government document for local authorities, which has a special chapter on H Iden but in a very broad sense of hazards. Examples are natural hazards such as tornado, flooding, earthquake; technological hazards like high pressure gas mains, computer systems failure; biological hazards including disease amongst people, animals or plants; and civil / political hazards comprising terrorism and civil unrest.	The publication is not specifically for landfills. It just encapsulates all natural and anthropogenic hazards without presenting any H Iden procedure or computer modelling. The format is more like a checklist. All the elements from 1 to 7 (above) are absent not only for landfills but any hazard in general.
CMSA, 2004; Puncochar,	These publications are regarding H Iden in the context of these respective subjects: mining,	These publications are not for landfills. All the elements mentioned above from 1 to 7 are absent from the landfill

2003; Koivisto, Tormakan-gas and Kauppinen 2001; Feldman and White, 1996; CHEM Unit, 2003; Pauluhn, 1999; and Tarazona and Vega, 2002	workplace, genetically modified organisms, neurology, indoor environment, ecology, toxicology, and chemicals. They all describe H Iden for the list of subjects above to various levels.	leachate perspective.

3.5 Exposure Assessment (Ex A)

Table 3.4 shows that the current literature and computer models, discussed in Chapter 4, regarding risk analysis and exposure assessment are currently just adequate to meet the existing legislation requirements such as drinking water standards (EPA, 1980; 1988b; SEPA, 2005b). As explained below, however, in future this may not be adequate enough to meet the legislation requirements constantly becoming tighter, stringent and holistic by the day. The literature mainly considers humans as receptors. Furthermore, in terms of the development of an overall exposure assessment procedure, there is a lack of attention given to some other aspects, such as:

- Receptors other than humans, e.g. fish, algae, crops, terrestrial mammals / wildlife, ecological habitat.

- Natural and yet non-living receptors such as land, soil and air.

- Built environment comprising e.g. man-made ponds, buildings, utility crossings, and other structures.

- Statistical descriptions for maximum and mean exposure quantification, in order to assist with measuring risks for worst case and most likely scenarios, respectively, in a risk analysis process.

- Water courses (other than consumed by humans for drinking) such as rivers of various water grades (SI, 1994b).

The above listed areas become more important as environmental legislation is implemented that is more stringent, versatile and integrated, and yet the legislation is expected to become even more so in the future. For instance, the Water Framework Directive (EC, 2000) includes new requirements for protection and restoration not only of ground waters but also surface waters and dependent ecological systems (Environment Agency, 2003a). The Habitat Directive (EC, 1992) brings legal obligation to combat hazards in order to guard and enhance natural habitats and wild fauna and flora. The Landfill Directive emphasises on protection of not only hydrosphere but also geosphere as well as atmosphere. Thus, more integrated approach towards exposure assessment and risk analysis is required.

On the other hand, the current literature accounts for different aspects of exposure analysis to different levels of detail but none of them is complete enough from the perspective of landfill leachate. The research works presented in various publications are mutually independent and non-integrated. Some publications (e.g. Redfearn et. al., 2000) focus on humans as receptors and only consider the inhalation exposure route. Some publications are limited in their considerations of hazards, as covering all possible hazards is not in their remit (e.g., Moschandreas et. al., 2002 focus only on Particulate Matter (PM) hazard). In some publications, only multi-media and multi-pathway exposure and risk assessment of contamination due to an industrial facility were discussed (e.g. Bagli and Spadoni, 2000). Some publications (such as Eduljee, 1998; DoE, 1995b) consider exposure analysis in a general context and focus only on humans as receptors. Some literature concentrates on exposure from contaminated land perspective and not specifically landfills (Butt and Oduyemi, 2002). Further details are given in Table 3.4. In summary, there does not exist such an exposure assessment procedure, which allows integrated considerations of all the five factors listed in the first row of Table 3.4 for all environmental receptors, both living and non-living, via all exposure routes specifically for landfill leachate.

Table 3.4: Literature Review Examples: Discussing elements of exposure assessment present and absent.

Publication	Elements Present	Elements Absent
ICE, 1994	This publication describes risk assessment from the perspective of contaminated land rather than specifically from landfill's perspective. This publication just outlines the main contents of exposure assessment for any type of contaminated land, but does not present a robust and objective procedure of carrying out exposure assessment for landfills or any contaminated land with items as listed in the adjacent column 3 of this table.	The term 'elements absent' means knowledge gaps and limitations in the research works to date regarding exposure assessments from the perspective of landfill risk analysis. 1. The identification and categorisation procedure of pollutants at source (i.e. a given landfill), pathways (including exposure medium and exposure routes such as ingestion, dermal, inhalation), and receptors / targets is absent. 2. A procedure for measuring or quantifying exposure of receptors to hazards, covering all possible exposure routes via which hazards possibly can enter receptor boundaries. A function or facility that allows exposures from various individual exposure routes to be aggregated for a given receptor exposed to a given hazard. This function is provided in the computer model described in Chapter 6. 3. Significance of and likely uncertainties involved in the

		elements, particularly exposure measurement, indicated above. Units of exposure are not described in detail and no facility for landfill assessors to choose or opt from. Such features are provided in the computer model explained in Chapter 6. 4. Provisions in the exposure assessment system to assist with measuring both worst case and most likely risk scenarios. 5. The concepts of maximum, mean and minimum exposures as integrated in the computer model presented in Chapter 6. In other words, engagement of statistical descriptions that can help address issues of uncertainties, and temporal and spatial variations.
CIRIA, 2001	This publication is only for closed landfill sites. The publication contains a chapter specifically on risk assessment, which also contains a brief section on exposure assessment where main factors of exposure assessment are only mentioned.	There is no procedure for exposure assessment.
Environment Agency, 2003a	Provides guideline for landfill risk assessment and only for groundwater as receptor. Identifies some	Though a guideline on landfill risk assessment exists but it is not for considering receptors other than groundwater. Though

	fundamental requirements of risk assessment on, for example, geology, hydrogeology, and site investigation.	this publication relates to risk assessment for landfill leachate, but it is not holistic in the form of a methodology or ready to use procedure. There are no considerations of risk and exposure quantification. The computer modeling aspect of the publication (i.e. LandSim) is discussed in Chapter 4.
DETR et. al., 2000	As the document states itself that it provides material, in general, for the development of risk analysis guidance to assist issues like contaminated land, waste management, major accident hazards.	The publication addresses a range of issues in general (listed in the left column) but not specifically for landfills or landfill leachate. The objective of this publication is not to develop an integrated exposure assessment to assist quantitative risk analysis. In summary, in the context of landfill leachate all the five elements 1 to 5 above are not in the remit of this publication.
DEFRA and Environment Agency, 2002	This publication relates to exposure assessment for humans from contaminated lands. Details on various aspects of exposure assessment are given. Examples are exposure parameters (such as exposure duration, frequency), soil release, and transfer mechanisms, exposure equations, human activities and ages, exposure routes, various land-uses.	Deals in detail with humans as receptors, but not other environmental species and eco-systems. Element number 5 above is also not there. It is not specifically for landfill leachate. It is for contaminated land in general.
Environment	This document briefly addresses a broad and diverse	A holistic exposure assessment procedure accompanied with a

Agency, 2004	range of facets of landfill risk analysis along social, technical, environmental, economic and legislative and managerial themes. Both landfill gas and leachate are addressed. The main scope of the guidance is limited to five areas of risk analysis, which are accidents and their consequences; hydrogeology; landfill gas; particulate matter; and stability. The document briefly touches on elements like source, pathway and receptors yet not as parts of exposure assessment system.	corresponding computer model is not in the remit of this publication. There is no allowance for exposure quantification. Statistical descriptions aspects like maximum, mean and minimum exposures are not in the scope either. As the document states itself that there are five main areas, which constitute the main remit of the guidance (listed in the left column). Yet landfill leachate is not one of them though is addressed to an extent. The guidance also mentions that it does not provide all the detail needed to conduct risk analysis for a landfill and the same holds for exposure assessment.
Gregory et. al., 1999	This publication is for risk analysis of landfill gas only. Concerns mainly humans as receptors. Engages with some risk assessment modules such as gas generation, human exposure assessment with quantification aspect, pollutants' migration.	The risk quantification aspect is absent. It is not for landfill leachate. Element 5 above is not embedded, even for landfill gas. From a leachate perspective, all 5 elements above are absent.
Moschandreas et. al., 2002	Focuses on one type of hazard i.e. Particulate Matter (PM) and only in air as an exposure medium. The only exposure route accounted for is inhalation and considers only humans as receptors.	Does not present exposure assessment as an overall procedure and specially element 5 above is not included. This publication is not specifically for landfills. As mentioned in the corresponding left adjacent cell, consideration of types of hazard, exposure medium, exposure route, and receptor is

		very limited.
Bagli and Spadoni, 2000	This publication takes account of industrial facilities as pollutant source and humans as receptors. It touches on various aspects of exposure assessment including exposure routes, equations and quantification. Also briefly writes about risk assessment in the light of GIS (Geographical Information System).	It is not for landfills at all. Exposure assessment is not given as an overall procedure. Receptors other than humans have not been included. In the context of landfill leachate all the five elements mentioned above are absent as well.
Redfearn et. al., 2000	This publication, which is a paper, is related to risk assessment and thus also briefly mentions exposure assessment. However this publication is related to landfill gas and not leachate. Thus, it focuses on exposure route of inhalation only. Also, it identifies some sensitivities and uncertainties associated with exposure assessment.	Apart from a very limited section on exposure assessment, there is no procedure for describing how to perform exposure analysis process. All the five elements mentioned above are absent from the perspective of leachate. Although the first four elements are partly addressed to an extent, the consideration is from the landfill gas perspective.
DoE, 1995b	This publication portrays exposure assessment in a holistic manner, more than any other literature studied to date. However, the focus is not all environmental receptors but human health only. Similarly, not all pathways have been included, but	Does not present an exposure assessment procedure in a holistic manner, in the form of a computer model. Does not take account of all environmental receptors such as flora and fauna, but only humans. With reference to point 2 above, this publication does not seem to have a facility where all

	only six exposure pathways which are there to represent most risks to human health from landfills.	individual exposures via various corresponding individual exposure routes, could be summed up to determine total exposure for a given receptor exposed to a given hazard. Does not take account of statistical aspects as indicated in point 5 above.
Eduljee, 1998	A procedure on exposure assessment has been outlined which covers elements like 1 and 2 (listed above) to various levels of detail. However, only humans have been considered as receptors.	No computer model exists for the exposure assessment procedure in a holistic manner. Elements 3, 4 and 5 above are absent and element 2 is addressed to a limited extent. The procedure presented excludes various environmental receptors such as flora, fauna and the built environment.
Asante-Duah, 1996	Encircles all important aspects of risk analysis and management (including exposure assessment) of contaminated lands, but not in the form of a methodology. The various aspects have been considered as independent of each other.	Not specifically for landfills. Also all the five elements above are absent.
Daugherty, 1998	Contains details not only of exposure but also those of sources (of hazards), pathways and receptors in separate chapters.	This publication, like others, does not depict exposure assessment in the form of a procedure that a risk assessor could use to measure exposure. The publication is not specifically for landfills. Moreover, all the five elements above are absent.

EPA, 1992; 1999a	These publications are purely for exposure assessment. Thus, they encircle the subject from many different perspectives including not only aspects of hazards, pathways, receptors and exposures, but also types of doses (e.g. potential dose, intake dose, applied dose), exposure dose relationships, uncertainty assessment, individual and population exposure, exposure analysis in epidemiological studies, and position of the exposure assessment itself with respect to risk characterisation.	Although these publications focus purely on exposure assessment, the documents do not portray a holistic procedure for carrying out exposure analysis. Neither specifically for landfills nor for any other environmental risk analysis. All the five elements above are absent in the publication from the landfill perspective.

3.6 Concentration Assessment (CA)

The review of the literature shows clearly that the concentration assessment is a common part of a risk assessment process. The requirement of the CA in a risk assessment process is so important that it has to be carried out irrespective of the environmental field of application. The reason is that the degree of hazard is not dependent only upon the nature of a given hazard but also equally significantly it depends upon the concentration of the hazard received by a receptor (or target). For instance, if a hazard or pollutant is very dangerous but its concentration in a given scenario is well below safety level, then there is no risk. On the contrary, if a hazard is not very dangerous by its nature but it concentration is well over threshold, then the hazard is definitely posing high risk.

The literature studied to date does not cover the CA, except in a few cases. In these few cases, the CA has been covered indirectly to different degrees. For instance, some literature have been found to include the CA to the extent of threshold levels of concentration and / or mentioning of its place in exposure equations (See Table 3.5 below). Moreover, risk assessment approaches regarding landfills appear to lack the application of mass balance themes to exposure media and target boundaries. Such mass balance themes or equations are established in Chapter 5 and a real landfill scenario, discussed in Chapter 7, also points out that such mass balance approaches are not applied to the exposure medium and receptor boundary. The literature on the CA to date is very limited, indirect and is in a piecemeal manner. Brief remarks on the review of some of the literature and the knowledge deficiencies identified are contained in Table 3.5 below. From the table it can be safely concluded that, in the reported literature, no evidence has been found by the author on how to perform an analysis of hazard concentrations as a part of a landfill risk assessment. Furthermore, no evidence has been found for any landfill risk assessment approaches involving the CA as an entity, even though landfills in the UK are now risk assessed under the Waste Management Licensing Regulation, 1994 (Butt and Oduyemi, 2003).

Table 3.5: Literature Review Examples: Discussing elements of concentration assessment present and absent (Butt and Oduyemi, 2003).

Publication	Elements Present	Elements Absent
Asante-Duah, 1996	Briefly discusses assessment of concentrations of pollutants under the heading of toxicity assessment. In the context of concentration assessment defined in this paper, the discussion in the publication goes only as far as mentioning the philosophy of threshold levels of doses (named reference doses in the publication and critical concentrations in this paper). The rest of the discussion in the publication was on other aspects of toxicity and exposure rather than concentration assessment.	A range of elements are absent including the following: 1. The concentrations of pollutants at source (i.e. landfill), pathway and target are absent. 2. The Initial (or Background), Reaching (or Incident), Intake and Final concentrations for both pathway and target, are absent. More details in Chapter 4. 3. There are no measuring procedures of the concentrations mentioned in 2 above, at the source location, along the pathway and at the target location. 4. Significance of and likely uncertainties involved in the elements indicated above. 5. Units of concentrations of pollutants are not in the remit of this publication. A button is provided for these in the RA computer model presented in Chapter 6. 6. The concepts of Maximum, Mean (or Most Likely) and

		Minimum concentrations at source location, along the pathway and at the target location. This is further explained in Chapters 5 and 6.
EPA, 1992	Describes general exposure equations in which concentration of a hazard in the exposure medium for a target (e.g. human) is required.	No method on how to estimate this hazard concentration in the exposure medium was established. In addition, all the six points mentioned above are absent.
Asante-Duah, 1993	This discusses different aspects of acceptable concentration levels and philosophy of doses to living targets in the context of toxicology, which can be helpful in identifying critical concentrations for different scenarios.	No procedure is described for concentration analysis, as part of a risk assessment process. All the six elements described above are absent.
Hallenbeck, 1993	Same as Asante-Duah, 1993	Same as Asante-Duah, 1993
ICE, 1994	Discusses different aspects of the environmental risk assessment process to various degrees of incompleteness.	Irrespective of the degree of completeness of risk assessment, this publication does not cover the concentration assessment at all, which is an important stage of a risk assessment process. All six elements described above are absent.
WDA, 1994	Same as ICE, 1994 above.	Same as ICE, 1994 above.
Daugherty,	Same as ICE, 1994 above.	Same as ICE, 1994 above.

1998		
Environment Agency, 1999; 2003a	Briefly covers the critical concentration aspect of concentration assessment, only by describing threshold levels of contaminants e.g. in drinking water. It also suggests using LandSim model to probabilistically estimate concentrations of pollutants as they migrate from a given landfill to hydrogeosphere e.g. groundwater abstraction point. The LandSim is discussed in Chapter 4. However, LandSim can be used to estimate pollutant concentrations that could reach an exposure medium such as groundwater, river, etc.	Did not discuss concentration assessment at all. Apart from the feature of LandSim estimating pollutant concentrations reaching a given exposure medium in hydro-geosphere, all the elements described in the six points above are absent in the publication.

3.7 Other Sections of the Risk Assessment

The other four sections of the RA are significance assessment (Sig A), uncertainty assessment (UA), migration assessment (Migra A), and risk characterisation (R Cha). The Sig A and UA are common to all modules, sub-modules and parameters of the RA and have been discussed above in Tables 3.1 and 3.2 of the RA and HA, respectively. Similarly the status of the Migra A and R Cha sections of the RA in the literature is already addressed in Table 3.1 above. Further details on these four sections and their location in the RA methodology are illustrated in Chapter 5.

Chapter 4

THE STATE OF THE ART – COMPUTER MODELLING

This chapter studies various computer models relating to environmental risk assessments. The chapter highlights limitations of these models in relation to risk analysis overall as well as hazard assessment as an individual entity in itself whose quantitative output is input to the risk estimation and assessment. These models are also analysed at the level of individual risk analysis items (including baseline study, hazard identification and categorisation, exposure assessment, and hazard concentration assessment) in order to further establish how developed these individual constituents of risk assessment are from the point of view of modelling. There is bound be some repetition below when more or less same models are considered not only for hazard assessment and risk analysis but also for the individual constituents. The review of the models also refers to the relevant sections in Chapter 3 where necessary.

4.1 Risk Assessment (RA)

The development of computational methods and the ability to model systems more precisely enables hazards to be quantified, their effects to be simulated and risk analysis to be pursued with greater accuracy, leading to a more effective risk management. These developments are not only important for all areas of human endeavour, but have particular relevance to environmental issues where the risks involved are increasingly seen as substantial. However, the review of current computer models did not find a risk assessment computer model that addresses the knowledge gaps indicated in Section 3.1, Chapter 3 (McMahon et. al., 2001; Butt et. al., 2006a; 2008, in press – a). It should be noted that in this research work a computer model is seen as an electronic representation of a method or procedure.

An investigation of the various relevant computer models that are recognised to be closely related to landfill risk assessment was undertaken. Namely,

- LandSim (Environment Agency, 1996; 2001; 2003e),
- HELP – Hydro-geological Evaluation of Landfill Performance (Schroeder et. al., 1994; FPLC, 1997; Scientific Software Group, 1998; UCF, 2001),
- GasSim (Attenborough et. al., 2002; Golder Associates, 2003),
- GasSimLite (Environment Agency, 2002),
- RIP – Repository Integration Programme (Landcare Research, 2003; Golder Associates, 1998), and
- 3MRA – Multimedia, Multipathway, and Multireceptor Risk Assessment (EPA, 2004a)

The first four computer programmes are specifically designed for landfills, although the features of the RIP were subsequently extended to take landfills into account on a comparatively large scale and 3MRA is not only for landfills but other waste management issues as well. The other software types examined are not demonstrably related to landfill risk analysis, although they could be used to underpin some of the aspects of landfill risk assessment. For instance, Drill Guide (Scientific Software Group, 1997/98) is useful in the sense that it can be included in the geology module of the baseline study of a given landfill, which consequently will help in the risk assessment process.

As far as the software packages specifically on landfill risk assessment are concerned, they do not holistically encapsulate all the elements of RA methodology for landfill leachate. For example, the LandSim software, which is purely for landfill risk assessment, probabilistically estimates likely concentrations of leachate pollutants that can reach a given point in the ground (e.g. groundwater abstraction point) in a certain time in terms of years. It also allows for temporal and spatial variations. However, it does not include the quantification aspect of exposure analysis, for instance, what would be the amount of exposure for people (or livestock) if they were to consume this groundwater. However, the LandSim's characteristic of pollutant concentration estimation in an exposure medium such as groundwater can be taken a step further to quantify exposure (e.g. for live-stock or a fish farm), which would make the quantitative risk assessment more comprehensive. This is one of the features, which this research study has attempted to take into account (Chapters 5 and 6). Furthermore, the LandSim is a tool mainly focusing on groundwater as a receptor and not particularly other environmental receptors like human population, livestock, or crops in a farm field. Thus, LandSim is a part of the total RA not the total RA model itself (Robinson, 1997). Similarly, the HELP programme contains only some aspects of landfill risk assessment. These are mainly the design features of landfill (such as liners, capping) and some of the baseline study aspects (like precipitation, surface runoff), with it not addressing many other RA modules and sub-modules. The software GasSim, although dealing with relevant risk assessment modules, including gas generation, migration, impact and exposure, as its name suggests, is designed for assessing landfill gas and not leachate. The GasSimLite is also developed from the perspective of landfill gas only and is used for calculating gas emissions. As with the other models mentioned, both GasSim and GasSimLite do not offer 'total' RA models in a categorical and algorithmic manner even for landfill gas.

On the other hand the RIP, which is an integrated probabilistic simulator for environmental systems, has not been specifically developed for landfill risk assessment. It has been designed generally for any potential pollutant source in the ground such as a chemical storage tank. So with the RIP, which is a generic software, risk assessors have to adapt it to their specific problems including landfills. This adaptation is time consuming and not easy (Miller, 1998). Although RIP can be applied to landfills for issues like contaminant release and transport, it does not readily provide such a straightforward total RA procedure for landfill leachate, which a risk assessor could follow in a sequential and systematic fashion. GoldSim is another general-purpose simulation software to support an even wider variety of applications most of which fall into one of the following three categories: environmental systems modelling, business and economic modelling, and engineered system modelling (GoldSim Technology Group, 2003). Thus it outgrows even the RIP in terms of generics. And in parallel to RIP users have to learn how to adapt the GoldSim to their specific problems.

The EPA's Multi-media, Multi-pathway, and Multi-receptor Risk Assessment (3MRA) allows for evaluation of five waste management unit types and landfill is one of them. The other four are waste pile, aerated tank, surface impoundment, and land application unit (Leavesley and Nicholson, 2005). Thus, this renders the model more general than if it had been only specific to landfill leachate. The model does not include the complete set of exposure routes. For example, some human exposure pathways like dermal exposure are not included, nor is the potential for adverse effects beyond a two kilometre radius around waste management units. Also, concurrent exposures to multiple contaminants in the waste are not considered (EPA, 2004a). The model encapsulates a host of living receptors but does not seem to mainly include non-living items as standalone receptors though may be indirectly covered as part of ecological systems (CEAM, 2005; Weinberg et. al., 2003).

The ConSim programme is a tool for assessing the risks that are posed to groundwater quality by pollutants migrating from contaminated land (Whittaker et. al., 2001; Golder Associates, 2004). The author finds that this has not been specifically designed for use with landfills; particularly when landfills have a leachate head and / or liners, which is very likely with modern engineered landfills (Environment Agency, 2003f). The CLEA (Contaminated Land Exposure Assessment) software considers risks posed by hazards to human health only and not to other environmental receptors such as plants, animals, buildings and controlled waters (Environment Agency, 2003g). Pathways are considered only from the perspective of soil as an exposure medium and not leachate (Environment Agency et. al., 2002). As for ConSim, the CLEA programme has been designed for use with contaminated land and not specifically for landfills (DEFRA and Environment Agency, 2002) and once again, neither ConSim, nor CLEA offer a complete RA model for landfill leachate or even contaminated land.

The HWIR (Hazardous Waste Identification Rule) methodology represents the manner in which a United States national-scale assessment of human and ecological risks is determined for establishing appropriate contaminant-specific exemption levels for relevant industrial waste streams. The HIWR modelling technology has also been developed to automate the risk assessment methodology. The objective of the HIWR system is to reduce the possible over regulation. Thus waste streams which qualify HIWR rule, i.e. listed wastes that could meet the HIWR exit level criteria (in a given scenario), would no longer be subject to the hazardous waste management system specified in RCRA (Resource Conservation and Recovery Act, United States). This way HIWR can assist in sustainable waste management by supporting waste minimisation and the development of innovative waste treatment technologies. The HIWR approach covers a variety of living receptors like soil fauna, mammals, plants but does not seem to address non-living items as receptors in themselves. The focus appears to be on wastes themselves rather than landfills (DOE, 1994b; NERL, 2001; EPA, 1999b; 1999c; 2000b; 2003a; 2005).

SADA (Spatial Analysis and Decision Assistance) is a software that incorporates tools from environmental assessment fields into an effective problem solving environment (TIEM, 2006). These tools include integrated modules for visualisation, geo-spatial analysis, statistical analysis, human health risk assessment, ecological risk assessment, cost / benefit analysis, sampling design, and decision analysis. Out of this wide range of tools or modules, only two most relevant are selected to describe here as examples. The Human Health Risk module provides a full human health risk assessment and associated databases from a range of landuse scenarios. These include residential, industrial, agricultural, recreational, and excavation *but not specifically landfills.* Ecological Risk is another module or unit of the SADA which allows users to perform benchmark screenings and the ability to calculate forward risk to a number of terrestrial and aquatic receptors that are currently being added. Even after this module has been fully developed, it may only be helpful to an extent to address only two aspects of landfill risk assessments. Firstly, assisting in identifying the whole range of environmental receptors (both aquatic and terrestrial) and yet for humans as receptors, the user still will have to consult the former module, i.e. Human Health Risk module. Secondly, in establishing critical concentration levels which is only a factor of the Concentration Assessment section of the total Risk Assessment Methodology presented in Chapters 5 and 6. It seems that SADA is a bunch of a number of software packages addressing different scenarios. A landfill assessor will have to work on picking the right combinations of these different software each time they are carrying out a landfill risk analysis and yet SADA will not provide for each and every facet of the landfill risk assessment in a readily useable format. Moreover, as the title speaks for itself, the focus of the 'Spatial Analysis and Decision Assistance' appears to be more on spatial than temporal.

ARAMS (Adaptable Risk Assessment Modelling System) is a computer-based, modelling and database driven analysis system developed for the US Army for estimating the human and ecological health impacts and risk associated with military relevant compounds (MRCs) and other constituents (ERDC, 2006). ARAMS takes various existing databases and models for exposure, intake / update, and effects (health impacts) and incorporates them into conceptual site-models. The user may need to choose which particular model and / or database to use for each scenario. The heart of ARAMS is the object-oriented Conceptual Site Model (CSM) but that relies yet on another computer programme called FRAMES discussed below. Thus it is not an easy task to adapt ARAMS into a landfill leachate scenario every time if a landfill assessor decides to use ARAMS. Moreover, ARAMS appears to concentrate mostly on the exposure assessment facet of a risk analysis, which is just a part of the total risk assessment methodology presented in Chapters 5 and 6. It does not have other facilities such as a baseline study section comprising, for instance, geology, hydrology, hydrogeology, topography, etc. that are necessarily required in a landfill risk analysis. Similarly, MEPAS (Multimedia Environmental Pollutant Assessment System) is another computer-based programme which is a suite of environmental models developed to assess contaminated environmental problems for government, industrial, and international clients (PNNL, 2006a). The software integrates transport and exposure pathways for chemical and radioactive releases to determine their potential impact on the surrounding environment, individuals, and populations. MEPAS modules have been integrated in the FRAMES software platform to allow MEPAS models to be used with other environmental models to accomplish the desired analysis. In the context of landfills, the situation with MEPAS is not much different than ARAMS. Both the computer programmes are not to and do not present an overall risk assessment methodology of landfill leachate with the intent of holism.

FRAMES (Framework for Risk Analysis Multimedia Environmental Systems) is a software platform for selecting and implementing environmental software models for risk assessment and management problems which may even include electronic governance issues (Evangelidis, 2003). In other words, the purpose of FRAMES is to assist users in developing environmental scenarios and to provide options for selecting the most appropriate computer codes to conduct human and environmental risk management analyses (PNNL, 2006b). This program is a flexible and overall approach to understanding how industrial activities affect humans and the environment. It incorporates models that integrate across scientific disciplines, allowing for tailored solutions to specific activities, and it provides meaningful information to business and technical managers. FRAMES is the key to identifying, analysing, and managing potential environmental, safety and health risks. As is obvious with this discussion that FRAMES is a hugely generic programme, and yet it does not contain a software for landfill leachate which could guide a landfill assessor to perform a landfill risk analysis with the wide range of risk assessment features listed in Section 3.1, Chapter 2.

The RESRAD is a combination of two words RESidual and RADiation (DMS, 2006), which is used as an acronym for Residual Radiation environmental analysis (Farlex, 2006). The RESRAD is a family of computer codes to provide a scientifically based answer to the question 'how clean is clean' and to provide useful tools for evaluating human health risk from residual contamination (EAD, 2006a). These codes include (EAD, 2006a; 2006b):

1. RESRAD, for soil contaminated with radio-nuclides;
2. RESRADBUILD, for buildings contaminated with radio-nuclides;
3. RESRAD-CHEM, for soil contaminated with hazardous chemicals;
4. RESRADBASELINE, for risk assessments against measured (baseline) concentrations of both radio-nuclides and chemicals in environmental media;
5. RESRAD-ECORISK, for ecological risk assessments;
6. RESRAD-RECYCLE, for recycle and reuse of radio-logically contaminated metals and equipment; and

7. RESRAD-OFFSITE, for off-site receptor dose/risk assessment.

From the above it is obvious that none of the family members is specifically for landfill leachate, although RESRAD addresses wide-ranging environmental issues and aspects. Even if these members are used in combination, these are not able to address all factors and aspects of risk analysis of landfill leachate, for instance, landfill phases; detailed and categorical baseline study; etc. Furthermore, to combine these into a landfill leachate context alone would be a cumbersome task to execute each time a landfill risk assessment is performed for different landfill scenarios. However, there is no stopping landfill assessors to process landfill data sets using any of these seven codes (or, any other software, if suitable), while they carry out a landfill risk analysis following the holistic framework outlined in Chapter 5. For instance, RESRAD-CHEM considers nine exposure pathways including inhalation of dust and volatiles; ingestion of plant foods, meat, milk, soil, aquatic food and water; and dermal absorption from soil and water contact. This code may help address aspects of exposure assessment, which is only one unit of the total risk assessment process. However, this code is no longer being updated (EAD, 2006c).

RISC-HUMAN 3.1, RUM and Vlier-Humaan (Van Hall Instituut of Business Center, 2000; 2001 and 2002, respectively) are three other software packages relating to risk analysis with a main emphasis on exposure assessment. However, these are designed for use with contaminated land and not specifically for landfills. HAZUS 99 software regards earthquake issues whereas computer programmes HAZUS-MH (Multi-Hazards) are available for modelling hazards including wind and flood (FEMA, 2001; 2002; 2004). There are books on environmental modelling (such as Schnoor, 1996) which theoretically describe modelling to great details for air, water and soil but do not offer a complete and integrated computational system of risk analysis. There is a growing family of risk models that can help address different aspects and scenarios of risk in a piecemeal manner (CIWM, 2000). In summary, in the light of above investigation it is established that there is no holistic RA computer model for landfills that contains all RA modules, sub-modules and parameters along with the other features listed in Table 3.1 in Chapter 3.

4.2 Hazard Assessment (HA)

Due to the significance of HA alone (as described in the first paragraph of Section 3.2 of Chapter 3), this research study also reviews the computer models indicated in the above Section 4.1 from the standpoint of only HA. This is done in order to investigate current HA status as an entity in itself from the perspective of HA computer modelling. This investigation is laid down below. However, in order to reduce the degree of repetition, the following discussion does not describe what these computer models are themselves as such descriptions are already narrated earlier in Section 4.1. Therefore, a reader of this document is recommended to read above Section 4.1 in order to learn what these computer models themselves do.

The landfill related computer models including LandSim, HELP, GasSim, GasSimLite, and RIP were analysed particularly in connection to what degree these packages cover hazard assessment as a stand alone. The other software types examined are not demonstrably related to landfill hazard analysis, although they could be used to underpin some aspects of hazard assessment for landfills. As far as the software packages specifically for landfills are concerned, they do not holistically encapsulate all the factors of HA for landfill leachate. For instance, the LandSim being able to contribute to exposure assessment as well as hazard concentration assessment can be useful in quantitative HA. However, it does not address other facets such as exposure quantification. Similarly, the HELP programme contains only some aspects of which can constitute landfill HA, but is not to assist generating hazard indices in a quantitative manner for various sets of hazards, pathways and receptors. Both GasSim and GasSimLite are not for landfill leachate but gas. Moreover, they do not present holistic HA models in a categorical and algorithmic manner even for landfill gas. The RIP is a very generic model, which does not does not readily provide such a straightforward complete HA system for landfill leachate, which a user could follow in a sequential and systematic fashion.

Compared to the RIP, GoldSim is a software which is for even more general-purpose simulation as mentioned in Section 4.1 above. Thus GoldSim is not specifically for HA of landfill leachate. The same holds for the ConSim programme, which has been developed for contaminated land. The CLEA software assists exposure assessment, which is just one part of the total HA. Moreover, as for ConSim, the CLEA programme has been designed for use with contaminated land and not specifically for landfills. The HIWR approach does not offer a complete HA framework that could be integrated with the risk characterisation stage in order to accomplish the whole of the quantitative risk analysis for a given landfill scenario. In summary, the above investigation is concluded like this. There is no total HA computer model that contains all the A modules and sub-modules and satisfy the other features which are listed in Chapter 3 in Section 3.2 and Table 3.2. Since there does not exist a holistic HA procedure in the first place (as concluded in the previous chapter) therefore there does not exist a corresponding computer model either, as for the latter to be designed the former has to be developed beforehand.

4.3 Baseline Study (BA)

A strategic computer-aided procedure for carrying out baseline study for landfill leachate is one of the knowledge deficiencies identified in the state of the art. In this section some examples of computer models are considered with main focus on baseline study alone. The landfill related computer models including LandSim, HELP, GasSim, GasSimLite, and RIP were particularly analysed in connection to what degree these packages cover the baseline study section of RA and / or HA. While other software types studied are not landfill related. However, some of them could be used to cover some aspects of the baseline study as indicated with an example in the last sentence of paragraph 2 of Section 4.1 of this Chapter.

As far as the landfill related software packages are concerned, they do not address all facets of the baseline study. Some models cover aspects of baseline study in parts and to a limited level. For example, LandSim uses various input data to prepare site conceptual model. However, LandSim does not describe how to find and process the data, all of which form part of what has been referred to as 'baseline study' in this research study, i.e. comprising the eight modules mentioned in Table 3.1 in Chapter 3. Similarly, the HELP model although containing some aspects of hydrology, including precipitation and surface runoff, does not cover many other aspects of hydrology including evaporation, transpiration, interception and liquid wastes. It also does not involve some other important elements of baseline study such as geology, hydrogeology, landfill site history and wastes types. The same goes for the RIP, where as GasSim and GasSimLite are from the point of view of landfill gas and not to do with baseline study in landfill leachate context. Similarly, the other models including GoldSim, ConSim, CLEA, RISC-HUMAN 3.1, RUM, Vlier-Humaan, 3MRA and HWIR do not offer a complete computer-aided baseline study system. In summary, no computer model exists, which has a concise and compact baseline study procedure for landfill leachate to effectively underpin the RA and / or HA process (Butt and Oduyemi, 2000).

4.4 Hazard Identification and Categorisation (H Iden)

In parallel to the format of Chapter 3, H Iden is also studied alone to recognise its state in the context computer modelling. An investigation of the various relevant computer models regarding landfills as well as others was carried out. The list of the landfill related software is the same i.e. LandSim, HELP, GasSim, GasSimLite, and RIP. The LandSim software does not integrate all parts of landfill risk analysis, including that of H Iden. LandSim has a section entitled 'Leachate Inventory', where some default pollutants are listed with corresponding default concentrations, enabling a risk assessor to add more pollutants, as required. Despite this feature, it does not have the facility of hazards categorisation into, for instance, grouping into leachate properties and pollutants; process and / or layout hazards; potential harms (more explained in Chapters 5 and 6). Similarly, a strategic H Iden system is not in the remit of the HELP programme. The RIP, being a very general environmental computational programme, does not readily provide such a straightforward H Iden method for landfill leachate where a landfill assessor can identify and categorise hazards in a sequential and systematic fashion, creating an 'easy-to-refer' format for the later stages of the risk assessment process.

Despite being designed for landfill gas, the GasSim and GasSimLite programmes do not present a H Iden structure even for landfill gas, and nor they do for landfill leachate at all. HAZID is another computer aid for hazard identification but for process plants and not to do with landfills at al (McCoy, et. al., 2000). Similarly, the other models including GoldSim, ConSim, CLEA, RISC-HUMAN 3.1, RUM, Vlier-Humaan, 3MRA and HWIR, do not offer a complete computer-aided H Iden system. In summary, no computer model exists, which has an integrated H Iden approach for landfill leachate to effectively underpin the RA and / or HA process (Butt and Oduyemi, 2006a).

4.5 Exposure Assessment (Ex A)

Ex A is one of the crucial parts of hazard assessment as well as risk analysis. In order to have quantitative HA and / or RA, Ex A has to be quantitative as well. Like other RA sections, this is also studied as a separate entity on its own in the context of computer modelling to establish the state of the art. Despite LandSim, HELP, GasSim, GasSimLite, RIP and 3MRA are the computer simulation packages which concern landfills in particular. None of these have been found to holistically encapsulate all elements of exposure assessment for landfill leachate. However, some of the computer models deal with some aspects of exposure assessment for landfills. For example, the 3MRA technology includes a number of exposure routes but not dermal contact. The RIP does not readily provide such a straightforward exposure assessment procedure for landfill leachate where a landfill assessor could identify and categorise hazards at the pollutant source (that is a given landfill), pathways (mainly exposure media) and receptors. In the same manner, it also does not include statistical descriptions for maximum, minimum and mean or most likely exposure values (as illustrated in Chapter 6).

Similarly, the LandSim model can be useful to Ex A in terms of assisting to characterise exposure media like groundwater, but it does not allow for the quantification of exposure. On the other hand, exposure assessment does not fall in the scope of the HELP, GasSim and GasSimLite models. Both GasSim and GasSimLite are for landfill gas but not leachate, whereas the ConSim package is a tool for contaminated land and is not specifically for landfill leachate. Also, this model does not accommodate receptors other than groundwater only, which means this is very limited in terms of consideration of range of environmental receptors. The CLEA (Contaminated Land Exposure Assessment) model is relatively more to do with exposure analysis as the title speaks for itself, but again this is for contaminated land and not specific to landfill leachate (DEFRA and Environment Agency, 2002). Moreover, as stated earlier, this considers human health and not other environmental receptors such as plants, animals, buildings and controlled waters (Environment Agency, 2003f). Pathways are seen only from the perspective of soil as an exposure medium and not leachate (Environment Agency et. al., 2002). Other elements such as statistical descriptions to identify worst case and most likely exposure scenarios are also absent in the model.

RISC-HUMAN 3.1, RUM and Vlier-Humaan (Van Hall Instituut of Business Center, 2000, 2001, and 2002, respectively) are three computer models developed to address particularly the exposure analysis section of risk assessments. However, like the CLEA, they are for contaminated land and not specifically for landfills. Features such as aggregation of exposures and statistical considerations (as mentioned in Points 2 and 5, respectively, in the first row of Table 3.4, Section 3.5, Chapter 3 and further details in Chapter 5 and 6) are also absent. Only humans are considered as receptors in these software packages as the names of the models suggest themselves. Other potential environmental receptors such as watercourses and built environment have not been taken into consideration in these software packages. In summary, the investigation of computer models has not come across an integrated and comprehensive computer model of the exposure assessment and yet only specific to landfill leachate. Currently available computer models lack the elements indicated in the first row of Table 3.4 (Chapter 3), either completely or partly. Moreover, they do not present such a concise Ex A model for landfill leachate, which as a complete unit, could readily be assembled with the format of other modules and sub-modules of the total risk assessment (computer) model illustrated in Chapter 6.

4.6 Concentration Assessment (CA)

Exposure assessment (Ex A) and concentration assessment (CA) are very much related when it comes to quantitative risk analysis in particular. The latter provides information on concentrations, which is used to estimate exposures, employing exposure equations (details in Chapter 5). Having realised such an importance of this section of RA and HA, the CA is also investigated alone from the point of view computer modelling. Since CA is heavily related to Ex A, therefore the following discussion on CA may seem to have some repetitions from Ex A module section above. However, the following discussion is purely from the standpoint of CA.

The computer models, which are or which have potential to assist risk assessments of landfills, do not strategically encompass all elements of concentration assessment, though some of the computer models cover aspects of CA in parts (Butt and Oduyemi, 2003). For example, the RIP does not *readily* address spatial and temporal variations of concentrations of hazards in the landfill body, exposure medium and environmental receptors. Although, the RIP has features that embrace source, pathway and receptor, in terms of likely concentrations of hazards leaking from the source, migrating via a pathway and, reaching and entering receptors. However, there is a lack of systematic categorisations like initial / background concentrations of hazard concentrations in exposure medium and receptors; concentrations of leachate hazards reaching exposure medium and receptors; and final concentrations of hazards in exposure medium and receptors after leachate hazards have reached (further details in Chapter 5). The RIP is a very generic software package that does not provide a ready-to-use CA framework specifically for landfill leachate.

In the context of concentration assessment, the LandSim probabilistically estimates the likely concentrations of pollutants that can reach a given point in the ground (e.g. groundwater abstraction point) in a certain period of time. Like RIP, the LandSim also does not provide a holistic CA system (Butt and Oduyemi, 2003). Similarly, HELP can be helpful in hydrological modelling and designing of a landfill, for instance, likely leachate seepage off the landfill site. However, it does not have a framework for users to specify threshold / critical concentrations so that these could be compared with pollutant concentrations entering an environmental target body to establish hazard indices in the later stages of HA and / or RA. In summary, from the above examples of various software / computer models, it can be concluded that there has been found no evidence of a computational CA procedure which is complete and comprehensive and yet only specific to landfill leachate (Butt and Oduyemi, 2003). The computer models that exist lack the elements mentioned in Table 3.5, Section 3.6 of Chapter 3.

4.7 Other Sections of the Risk Assessment

The other sections of risk assessment (RA), which are four in number, include significance assessment (Sig A), uncertainty assessment (UA), migration assessment (Migra A), and risk characterisation (R Cha). Sig A and UA, being common to all RA items, need to be electronically accessible by all modules, sub-modules and parameters in a computer-aided RA framework. None of the computer models investigated in above sections have been found to have this facility. This feature, however, has been added in the RA computer model prepared in this research study (Chapter 6). In the same fashion, Migra A and R Cha, which are mainly parts of risk estimation stage of the RA have also not been found strategically accommodated specifically for landfill leahcate in any computer models. Section 4.1 above also draws on the status of these four RA sections from the point of view of computer modelling e.g. LandSim. Further details on these four factors and their location in the computational RA model (developed in this research work) are illustrated in Chapter 6.

Chapter 5

THE DEVELOPMENT OF A HOLISTIC RISK ASSESSMENT METHODOLOGY

From the perspective of landfill leachate, this chapter produces a more strategic and integrated methodology of quantitative risk analysis, thereby bridging a number of the knowledge gaps identified in previous chapters. It is should be noted that the theme of the chapter is to cover wholeness of the methodology in the form a fundamental framework without engaging much in-depth detail of all modules and sub-modules of the methodology. However, this methodology is transformed into a corresponding computer model in the following chapter where some more details will be considered.

5.1 Preamble

One of the crucial knowledge limitations has been that of a very user-friendly, sequential / stage-by-stage, categorical, comprehensive and yet integrated and quantitative methodology to perform risk assessment (RA) in a holistic fashion specifically for landfill leachate. An attempt is made to present a framework of such a quantitative RA methodology in an integrated and strategic format in which all parts and sub-parts of the risk analysis are algorithmically drawn together. The term 'holistic' implies an overall framework covering all constituents and facets of the risk assessment of landfill leachate from the beginning to finish. However, these constituents and facets are not addressed in full detail as this study considers more of the 'breadth' of the parts and sub-parts of the methodology. That is, wholeness in terms of the 'breadth' not the depth. However, the methodology still encapsulates the wide range of scenarios and landfill systems indicated in Chapter 2. For instance, the methodology can deal with any landfill and waste types, any geology and hydro-geology, any leachate, any hazards, any pathways, any receptors, any measurement methods, etc. More details are provided in Chapter 6.

The framework of the Risk Assessment Methodology (RAM) of landfill leachate is developed into two main parts. These are Hazard Assessment (HA) and Risk Estimation (R Esti). HA itself is consisted of four sub-parts. They are:

1. Baseline Study (BS)
2. Hazard Identification and Categorisation (H Iden)
3. Exposure Assessment (Ex A), and
4. Concentration Assessment (CA) of hazards

The R Esti is also divided into four sub-parts, which are:

5. Migration Assessment (Migra A)
6. Significance Assessment (Sig A)
7. Uncertainty Assessment (UA), and
8. Risk Characterisation (R Charac).

Thus the RAM comprises eight sub-parts in total. Like HA, Risk Esti is a crucial part of the quantitative RA methodology, which enables the output of HA to be converted to Risk Quantification. R Esti is that part of the methodology, which differentiates between Hazard Assessment and Risk Assessment (as explained in Chapter 2). One can say that process of RA is not new. What is new is the process of attempting to predict the potential for harm in the absence of any clear evidence that an effect has occurred or could occur, which is called Risk Estimation (LaGoy, 1994; Boguski, 2004). These eight sub-parts of HA and R Esti together are elaborated below with the help of Figure 5.1, which is placed at the end of the Chapter for the reason being that the figure is to be referred to all along the discussion in the Chapter.

5.2 Baseline Study (BS)

The Baseline Study is defined as the most preliminary step or the very first step of a hazard assessment or risk analysis process of landfill leachate in which all basic information / data are gathered, organised and analysed (Butt and Oduyemi, 2000). It is also the step on which the rest of the hazard and risk assessment process is based. In the case of landfills, the BS has to take account of a wide range of subjects (Three Rivers District Council, 2002). These subjects are categorised into eight modules. These are:

1. Geology
2. Hydrology
3. Hydrogeology
4. Topography
5. Meteorology
6. Geography
7. Site Management, and
8. Human Influences

Figure 5.1 gives a representation of the eight modules and their respective sub-modules. Desk study, site inspection and / or ground investigation are three main themes to gather information on these modules for a given landfill. In this study, the eight modules of the BS are only described very briefly to give an overall picture of how the BS and the eight modules have been developed in a holistic manner for the HAM (Hazard Assessment Methodology) and / or RAM (Risk Assessment Methodology). It is also worth mentioning at this stage that there may be some overlaps between the BS modules and sub-modules depending on site-specific characteristics of a given landfill scenario. This is because science subjects overlap and do not have very strict and solid boundaries of knowledge. For instance, precipitation is a common sub-module to the hydrology and meteorology modules of the BS (Figure 5.1). In such cases, it is optional for the landfill assessor to cover precipitation either under hydrology or meteorology.

In the geology module, the lithosphere is divided into three main layers. These are top soil, drift and rock. In this module, a landfill assessor will establish relevant properties for the three layers. The properties may include depth and area, volume, slope, minerals, orientation, porosity, fissures, density, and other geological properties. All such information will help the landfill assessor to identify a range of characteristics of a given landfill, including leachate migration direction, precipitation, percolation, and chemical reactions of leachate contents with minerals (e.g. sorption, adsorption). It is highly recommended that if the landfill assessor has no background in geology, then a geologist should be consulted (Butt and Oduyemi, 2000).

The hydrology module is divided into two main sub-modules. These are 'Atmosphere Waters' and 'Lithosphere Waters' (Figure 5.1). The former addresses waters in the atmosphere, such as precipitation (rain, snow, sleet), evapo-transpiration (i.e. evaporation and transpiration), and interception. The latter covers sub-modules including runoff, infiltration, percolation, ingress, and water courses. The water ingress implies the water entering a given landfill body via migration below the ground surface. This ingress could be in the unsaturated portion of depth of the landfill or the saturated portion. Therefore, this sub-module is further divided into saturated ingress (or egress) and unsaturated ingress (or egress), as shown in Figure 5.1. However, the water on the ground surface is addressed by the runoff sub-module, which was mentioned above as a sub-module of Lithosphere Waters. The issue of water courses (abbreviated as WC in Figure 5.1) is classified into surface water courses (such as ponds, rivers, lakes), and sub-surface water courses like vadoze, aquifer, perched groundwater (Spence, 2000). If a landfill assessor opts, sub-surface water courses can be addressed in the hydrogeology module of the BS (discussed below) instead of the 'sub-surface water courses' sub-module of hydrology module. This is another example of an overlap among modules and sub-modules of the BS. This overlap is between the hydrology and hydrogeology modules. Most of the information collated in the sub-modules of hydrology is necessary for the H Iden sub-part, to estimate leachate generation (See Section 5.3). This indicates how outputs of one module or sub-module can be an input to another module or sub-module of the RA.

The hydrogeology module, as the name speaks for itself, is a science subject that exists in the overlapping area between geology and hydrology modules of the BS. Thus this module is bound to have a few common areas between the geology and hydrology modules. However, the hydrogeology module is divided into three main groups. These are hydrogeological zones, ingress and hydrogeological properties. The first group takes account of three zones namely: vadose zone, phreatic zone, and perched zone. In each of these three zones, a landfill assessor is expected to collate information on, for instance, plan dimension, depth and volume of the zones; and then use the information to develop a hydrogeological conceptual model of a given landfill. Other hydrogeological properties such as hydraulic gradient, hydraulic pressure, permeability, groundwater flow rate and direction are covered in the third group of this module. The second group, 'ingress', has already been described above.

The topography module covers three issues, which are landforms / ground surface contours, natural environment, and built environment. Novel aspects have been added to the subject. This has been done by adding natural and built environment sub-modules to it in order to make the RA procedure relatively easy for practitioners to use. These two sub-modules have been covered under the topography module, as they are judged to be the closest possible option for accommodating the natural and built environments among the eight modules of the BS. This was in order to avoid having two additional separate modules and thus limiting the total number of modules of the BS to eight rather than ten. In the landforms sub-module, a landfill assessor needs to identify slopes of the ground surface in the direction of and away from the landfill. These slopes will assist in estimating water runoffs in the direction of and away from the landfill for the hydrology module above. This is an example of relationships between sub-modules of the RAM. The sub-module natural environment is useful in that it identifies natural species, including the location of plant life, wild life, and aquatic life (along with their respective nature and sizes) in the region with reference to the location of a given landfill. Other characteristics of non-living items, such as surface water courses and / or groundwater, have already been addressed in the hydrology module of the BS. Like the natural environment, in the built environment sub-module, items such as buildings, houses / residential areas, commercial areas, and their sizes and nature can be mentioned. The information from the natural and built environment sub-modules will be an input to the targets / receptors identification, which is one of the modules of the Exposure Assessment (Ex A) sub-part, discussed later in Section 5.4.

The meteorology module comprises entities such as wind speed and direction, degree of cloudiness and sun, air pressure, wet and dry bulb temperatures, humidity, precipitation and others. All such parameters vary temporally and spatially. For a more accurate RA, statistical description of the parameters may be needed such as maximum, minimum, average or most likely. Similarly, the geography module accounts for parameters such as the geographical location of a given landfill (like latitude and longitude). Other relevant geographical properties (such as tropical) can be considered for a given landfill under this module. The site management module covers a wide range of issues related to a given landfill site itself. These include, site history, site type, site location, site map and layout, site engineering (design and construction), environmental monitoring, waste management practices and other site operations such as waste handling, documentation, waste analysis, waste types land-filled, amounts of wastes, night cover, weigh bridge, wind screen and equipment management. In the module 'human influence' a landfill assessor can identify past, present and future potential influences by humans in the region around the landfill, which could be affected by the existence of the landfill. For instance, will there be any potential for quarrying, buildings construction, water abstractions and other developments in future or are such human activities already underway? What are the purposes of such construction and water abstractions? Are water abstractions for human consumption or industrial use? This module focuses on these aspects and the information gathered in this module can be used in the later stages of the RA exercise, for instance, to establish sensitivity of environmental receptors / targets.

5.3 Hazard Identification and Categorisation (H Iden)

In this study, from the perspective of landfill RA, the Hazard Identification and Categorisation (H Iden) is specified as the second step or stage of the RA process, following the first phase, the Baseline Study. In the H Iden all potential hazards of leachate, either pollutants (e.g. Hg, Cd) or properties (e.g. Chemical Oxygen Demand (COD), pH), are identified and categorised into groups (listed below) for a more comprehensive, effective and categorical RA (Butt et. al., 2006a). From the perspective of landfill risk analysis the definition of hazard has been stretched beyond being a substance only. It is defined as follows. A hazard means anything such as a substance, a property, a process or even a layout / setting that may cause harm(s) or has a potential to cause harm(s) (HSE, 1996b; 2003; EHSC, 2002). These groups include:

- Quality Hazard (pollutant or property);
- Quantity Hazard;
- Process and / or Layout Hazard; and
- Harms.

All these groups are modules of H Iden and further elaborated as follows. In the H Iden Quantity module a risk assessor is expected to estimate the quantity of leachate in a given landfill site. The quantity of leachate itself is deemed as a hazard in the H Iden and consequently in the RAM. The estimation of leachate quantity can be carried out by using an empirical method such as mass balance or water budget approach. This will involve factors including, precipitation, interception, evapo-transpiration, run-off, groundwater ingress, and liquid wastes, if any. The information on these factors will mostly come from the hydrology module of the BS. A risk assessor may not have to literally carry out an exercise of leachate quantification every time the RAM framework is being used as this information may already exist and may be held by a legitimate organisation, for instance, the Environment Agency in England and Wales.

After leachate quantity has been worked out, a risk assessor can switch to the H Iden Quality module of RA. In this module, hazards posed by leachate in terms of its qualities are characterised. This module is further categorised into two sub-modules namely, pollutants and properties. The former comprises the hazardous substances (such as cobalt, barium), which may exist in a given leachate. The latter, unlike substances existing in leachate in physical form, deals with the properties of leachate e.g. BOD (Biochemical Oxygen Demand), pH value (i.e. balance of acidity and basity), age of leachate, Hardness. In the H Iden Quality module, there is a facility for a risk assessor to categorise leachate qualities into groups of toxic, non-toxic or both. If the toxic category is chosen, then it can be further classified into carcinogenic, non-carcinogenic, or both categories (See Figure 5.1).

The third module of H Iden is 'Process and / or Layout Hazard'. This module specifies hazards in relation to processes and / or layouts in a given landfill scenario. Examples are groundwater level fluctuation, heavy rain, liners and capping failure or no liners and capping used, fissures in bedrock, high porosity of bedrock. In this module, a risk assessor is expected to consider all such items in the context of hazards posing risk or adding more to the degree of overall risk. Necessary information on all such items will come from the eight modules of the BS of the RA. It is worth noting that in some cases it may be difficult to differentiate between 'Process' and 'Layout'. For instance, the higher the groundwater level the more the hazard and risk, and this could be seen as a hydrogeological layout hazard. At the same time, this also depends on the fluctuation of the groundwater level over time, which is a hydrogeological phenomenon or process affecting the degree of the environmental hazard and risk. Similarly, application of liners to a given landfill or no liners is a matter of layout. However, their failure due to degradation over a time period may be described as a process. These examples explain why this module deals with both the process and layout.

The last and fourth module of H Iden module is Harms, which implies damage, loss, hurt, or injury. This module is not specifically about hazards. It specifies the potential harms that could come from the hazards that would have already been identified in the above three modules of the H Iden for a given waste disposal site. That is why this module is common to all the above three modules as shown in Figure 5.1. Also, it is the nature of a harm that assists in categorising a given leachate hazard. For instance, if harm from a hazard such as PCB causes cancer then PCB would be seen as a carcinogenic hazard. For more details on the Harms module see Section 6.3, Chapter 6.

5.4 Exposure Assessment (Ex A)

An exposure assessment process can be defined as that fundamental stage of landfill RA in which all possible hazards at the pollutant source, pathways and environmental receptors or targets are identified and categorised. In addition, exposures of the identified receptors to the identified hazards through identified pathways are measured.

The definition is further elaborated on in the latter paragraphs of this section where Ex A modules are described. The Ex A is seen as one of the most significant, important and effective factors of quantitative hazard and risk assessment, as the success of the latter is based on the former. The reason is that risk is not just a matter of hazard, pathway and receptor. The degree of exposure also plays a key role for a risk to exist. For example, if a hazard and a receptor exist, and the pathway has been manipulated in such a way that there is no exposure (i.e. exposure is zero) then the receptor faces no risk. Furthermore, in order to quantify risk in a risk assessment process, exposure of receptors to hazards has to be quantified as well. From the quantification point of view, this is another important link between the Ex A and RA.

The Ex A is divided into four main modules. These are:

- Source Identification and Categorisation;
- Pathway Identification and Categorisation;
- Receptor or Target Identification and Categorisation; and
- Exposure Quantification.

They are abbreviated as Sorc Iden, P Iden, T Iden and Ex Quan, respectively. This is shown in Figure 5.1. In the Sorc Iden module a given landfill is identified as a pollutant source. This module also allows the identification and categorisation of a given landfill into different parts in a number of ways. For instance, which parts of the given landfill are active, post closed and / or in design / planning stage; which cells have similar dimensions? In this module, a risk assessor can also identify, geometrically, an equivalent and effective centre point in a given landfill body. The distances to the receptors and exposure media can be measured from this centre point, as a landfill generally does not have regular dimensions. In the P Iden module a risk assessor identifies all likely / possible pathways connecting a given landfill with likely receptors in a given scenario. The main focus in this module is the identification of all links between the two ends of each pathway, i.e. between a given landfill (the pollutant source) and a considered receptor. Since the given landfill (i.e. source) and receptors are to be dealt with in their respective modules (i.e. Sorc Iden and T Iden, respectively), therefore they are not the main focus in P Iden. However, CEP (Conceptual Exposure Pathway) Model can be used to make P Iden module more comprehensive (Sara, 1994; DOE, 1998). From the perspective of a landfill leachate, some examples of pathway constituents are the unsaturated zone, saturated zone, aquifer, groundwater abstraction point, dermal contact, river, fish, and ingestion. More details are laid down in the RAM computer model, which is discussed in Chapter 6. In the T Iden module, a risk assessor categorically specifies all likely environmental species that could be affected by hazards in a given landfill scenario (See Figure 5.2). This will not be only humans, but other potential terrestrial and aquatic flora and fauna. Also these receptors may not necessarily be only living, but could also be non-living such as atmosphere, lithosphere / land, hydrosphere, buildings, structures. These receptors could be either off-site or on-site. The fundamental information for these modules in a given landfill scenario will come from the BS section where a risk assessor would already have gathered necessary information. For instance, topography module of the BS can assist in identification of potential environmental receptors; geology and hydrogeology modules can be helpful in establishing pathways.

In the fourth and last module entitled Ex Quan, there are a number of ways to quantify exposure. These depend upon quality, nature, type and size of data and information available. The quantification of exposure also depends on the nature of an individual receptor, hazard and pathway and their combinations. Such details are not covered to full depth within the scope of this study and left for future research. However, some exposure equations as examples are listed in Table 5.1. These are for an environmental assessor to consider and use when appropriate for living receptors like humans and other mammals. The exposure routes in the Ex Quan module, through which hazards could enter a given receptor boundary, have been divided into four types thereby employing holistic and integrated approach (Quamruzzaman, et. al., 2004). These are ingestion, dermal contact, inhalation and 'others if any' (Figure 5.1). For living receptors, like humans, there are three possible exposure routes. They are ingestion, dermal contact and inhalation. Ingestion does not only include drinking or eating, but also includes routes such as injection e.g. a patient in a hospital being injected with glucose directly in to his / her body. Dermal contact includes activities like, taking a shower, bathing and swimming. The exposure route of inhalation deals with breathing in some polluted air, gas and / or vapours, for instance, dissolved methane in leachate (Robinson, 2001). The fourth route has been entitled 'others if any', in order to provide a facility to the risk assessor to account for exposure routes other than the three indicated earlier. This fourth route is particularly useful in cases of non-living receptors. For example, a 'landfill leachate' polluted aquifer could lead to a situation where a river is seen as a receptor. Thus, the entrance of the landfill leachate hazards into the river via the aquifer will fall under the category of 'others if any' type exposure route. This also indicates the flexibility of the RA framework in terms of the variety of scenarios of environmental receptors it can accommodate.

Table 5.1: Some Examples of Exposure Equations

Intake (mg / kg / day) = [$C_{medium} \times CR \times CF \times FI \times ABS_f \times EF \times ED$] / [$BW \times AT$] (DEFRA and Environment Agency, 2002 and Asante - Duah, 1996), where: C_{medium} = Contaminant concentration in the exposure medium of concern (mg/m^3 for air; µg/L for water; or mg/kg for soil) CR = Contact rate (m^3/hr for air; mg/day for soil; or L/day for water) CF = Conversion factor FI = Fraction intake from contaminated source ABS_f = Bioavailability or absorption factor (%) ET = Exposure time (hours/day) EF = Exposure frequency ED = Exposure duration (years) BW = Body weight (kg) AT = Averaging time (days)
Intake = C_{medium} x IR x ED Is another and simple form of an intake or ingestion exposure equation (DEFRA and Environment Agency, 2002 and Daugherty, 1998), where: C_{medium} = Contaminant concentration in the exposure medium of concern (mg/m^3 for air; µg/L for water; or mg/kg for soil) IR = Also called 'contact rate' is amount of polluted exposure medium contacted or intaken per unit time or event. ED = Exposure Duration

The categorisation of exposure routes into the four groups above, i.e. ingestion, dermal contact, inhalation and 'others if any', allows for the addition of all individual exposures from these exposure routes to determine total exposure to a given receptor / target from a given hazard. It is worth mentioning that if a given hazard affects a specific organ of a receptor (such as a human stomach) via a specific exposure route (like ingestion), then other exposure routes can be safely neglected for such a case. If the values for exposure routes other than ingestion are still considered in such a case, then this will, however, add on a degree of 'conservativeness'.

In the Ex Quan module statistical descriptions can also be taken into account. These statistical descriptions include maximum, mean / median, most likely and minimum exposures. These statistical descriptions assist the quantification of both most likely and worst case scenarios of risk (further details in Chapter 6). As far as the modules Sorc Iden, P Iden and T Iden are concerned, these statistical descriptions are not applicable to them, because these modules are descriptive in nature. In statistical terms, these three modules contrast with the Ex Quan module, which is numerical and objective in nature.

5.5 Concentration Assessment (CA)

In the context of hazard and risk assessment for landfills, this research study defines concentration assessment as that fundamental stage of a risk assessment process in which concentrations of all possible hazards are estimated or measured in four categories. These are (Butt and Oduyemi, 2003):

- Concentrations of hazards at the pollutant source which is a given landfill;
- Concentrations across links or media of pathways, mainly exposure medium;
- Concentrations at the target location (both background and reaching (or intake) concentrations); and
- Critical (or threshold) concentrations against which hazard concentrations are compared and controlled.

The Concentration Assessment of hazards is seen as one of the most important and significant factors of a quantitative hazard and risk analysis. The reason is that the degree of risk is significantly dependent on the concentration of a given hazard that reaches a given receptor / target; enters the target's boundaries; and the safe and acceptable level of hazard concentration for the given target (Crawford-Brown and Brown, 1997; Washburn, 2005). Mapping on the four categories listed above, the CA section of RA is correspondingly divided into four modules. These are Source Concentration Analysis, Pathway Concentration Analysis, Receptor or Target Concentration Analysis and Critical Concentration Analysis. They are abbreviated as Sorc C, PC, TC and Cri C, respectively.

In Sorc C module, concentrations of 'leachate quality hazards', that is properties of and pollutants in leachate (identified by a landfill assessor in H Iden section earlier) are described. PC is further divided into two sub-modules, Pre-Ex MC and Ex MC, representing Pre-Exposure Medium Concentration Assessment and Exposure Medium Concentration Assessment, respectively. The former sub-module involves concentration analysis of hazards in all the links of a given pathway that lie between the landfill source and a given exposure medium of a given receptor. These links may include, for example, unsaturated zone, saturated zone, and aquifer or others, depending upon characteristics of a given scenario. The latter sub-module (Ex MC), however, deals specifically with the exposure medium for a given target, in terms of concentration analysis of hazards. Examples of exposure medium are groundwater abstraction point in an aquifer and a case where water flows from an aquifer to a river (Butt and Oduyemi, 2003).

Ex MC and TC are further divided into three sub-modules each as shown in Figure 5.1. Ex MC is divided into Ex MCi (Exposure Medium Concentration Initial or Background), Ex MCr (Exposure Medium Concentration Reaching) and Ex MCf (Exposure Medium Concentration Final). The first two of these sub-modules are to be added together according to the nature, size and concentration of the two streams, using a mass balance equation approach to estimate for the third sub-module. An example of mass balance equation is shown below. The following equation can be used to obtain the final concentration of a given hazard in the exposure medium (Ex MCf):

$$\text{Ex MCr} \times m_r + \text{Ex MCi} \times m_i = \text{Ex MCf} \times m_f \qquad (5.1)$$

Where, m_r , m_i , and m_f are masses of the exposure medium reaching, exposure medium initial and exposure medium final, respectively. If all streams are flowing then mass 'flow rate' balance equation can be used. For example, in case of an aquifer and river, both streams are flowing. For a static water course, there is a need for further research that falls beyond the scope of this study.

Like the Ex MC module, the TC module has also been further categorised into three sub-modules namely, TCi (Target Concentration Initial or background concentration), Intk C (Intake Concentration i.e. hazard concentration entering boundaries of a given target / receptor) and TCf (Receptor or Target Concentration Final). Like the case of Ex MC, the first two when summed up using a mass balance equation approach, gives the value of final concentration of a given hazard in the target (i.e. TCf). The mass balance has to account the nature, size and concentration of the two streams i.e. TCi and IntkC. The word 'nature' has been used in relation to whether it is a living receptor / target such as human, flora, fauna or non-living receptors such as water-courses (like a river which is dynamic or a lake which is relatively static). For example, consider Mercury (Hg) as a given hazard. In the case of river being the target it is necessary and practicable to consider Hg background concentration in the river. Whereas if the target is a living, for example a specific species of bird, then background concentration of Hg in bodies of the birds may not be significant and / or may be difficult to measure in a comparative manner. Like the case of Ex Quan module, all types of the concentrations mentioned above can be measured applying statistical descriptions. The consideration of maximum and most likely concentrations of hazards would assist in the estimation of corresponding maximum and most likely TCf values, and consequently Risk Quantification for most likely and worst case scenarios, respectively. This is explained further in Section 5.9.1 below.

It is worth mentioning that various terms have interchangeably been used in the literature to date to describe Critical Concentration, including safe limits, acceptable levels, standards, threshold levels and control limits. However, Critical Concentration values for a given landfill scenario are preferably obtained directly from legislation and regulations or may be obtained from government proposed guidelines (EPA, 1986; 2002b; SI, 1994b; Greenwood et. al., 2000; Dixon et. al., 2000; Bates et. al., 2001). They may also be determined from items such as Reference Dose (RfD) and Unit Cancer Risk (UCR) in the literature, depending upon the nature of the given scenario characteristics in general and that of a given receptor / target in particular (Butt and Oduyemi, 2003). Once Cri C and TCf values are established for hazards in a given landfill scenario, the process then can lead further to the R Esti stage of the RA comprising the following sub-parts.

5.6 Migration Assessment (Migra A)

Migration Assessment is that factor of the RAM framework which considers transfer and fate of (pollutant and / or property) hazards of a given landfill leachate via various media / links of pathways from the pollutant source, i.e. the landfill, to different environmental receptors. This consists of two main modules (Figure 5.1). These are:

- **Migration** which regards transfer of leachate as a physical phenomenon in itself. This module is to address aspects like dispersion, advection, retardation.

- **Attenuation** which considers variation of qualities of leachate as it moves through pathways. These variations could be due to biological, physical and / or chemical reactions (Gerke, 1999; Brusseau, 1999; Zhan, 1999). Examples are sorption (adsorption and / or absorption), cation exchange reactions, dilution.

In the light of the Sorc Iden, P Iden and T Iden modules of Ex A, the Migra A is to assist in estimating or measuring concentrations of leachate hazards not only at the landfill pollutant source itself but also other links of a pathway like exposure medium in particular. These concentration values are used in the Ex Quan module and CA's modules and sub-modules in the RA process. This is an example of how the RAM framework addresses the aspect of mutual information transfer between modules and sub-modules of the RA process, even backwards. A range of tools such as LandSim are available which a risk assessor may consider to use if appropriate and suitable to characteristics of a given landfill scenario to estimate likely hazard concentrations at, for example, a groundwater abstraction point over time. Consideration of temporal and spatial variations (like LandSim does to an extent using probabilistic approach) and employment of statistical descriptions (as described in Chapter 6) can assist to obtain more site-specific estimations.

5.7 Significance Assessment (Sig A)

The Sig A section of the RAM is descriptive. This is common to all modules and sub-modules of the RA framework. The Sig A does not directly contribute to Risk Quantification as such. The Sig A is to prompt a risk assessor mainly to establish parameters of the Risk Assessment that are of significance in relation to Risk Quantification for a given landfill. For instance, precipitation is much more important than interception loss; in which case could interception be more important or less significant that it can be ignored safely. At times significance may mean the same as the sensitivity. For instance if a groundwater course is for drinking purpose than the significance or sensitivity of this ground water as a receptor is far more than a groundwater course which is for a non-drinking purpose such as coolant for an industrial plant. Similarly, significance of all parameters engaged in various modules and sub-modules of the framework can be analysed and described. How the Sig A is linked with various RAM modules, sub-modules and parameters is described in the following Chapter 6 on RA model development.

5.8 Uncertainty Assessment (UA)

Immeasurable or non-estimated risk is called uncertainty. Uncertainties can arise from several sources, including natural or inherent variability over space and time, variability in the accuracy of measurements and data manipulation, and knowledge gaps due to lack of data. They can also arise when models and test systems do not accurately reflect the environment or exposed population of concern (DETR et. al., 2000; EPA, 2004b). The UA section of the RAM is to analyse uncertainties at different stages of the RA process for a given landfill. Like the Sig A, the UA is also common to all modules and sub-modules of the RA methodology. However, in the UA section of the RAM a range of different types of uncertainties are listed (see below) which a risk assessor can use as a checklist to consider uncertainties at various RA stages.

- Limitations of measuring instruments under the prevailing operating conditions;

- Data manipulation such as averaging out, the local variation in concentration of a pollutant hazard in a given landfill, variation in precipitation, groundwater level fluctuation;

- Data interpretation in the relevant literature (such as the reading and estimation from precipitation maps; extrapolation of animal data in toxicology, epidemiology, industrial hygiene, health physics);

- Spatial variations;

- Temporal variations;

- Knowledge gaps such as limitations of knowledge of toxicology todate; and

- Limitations of models being applied such as LandSim works more effectively if targets are not far from the pollutant source.

Ideally, all uncertainties involved in a risk analysis process should be estimated and accounted for where possible. Whether possible or not, in either case uncertainties at all RA stages involved in all parts and sub-parts of the RA should be clearly described to assist decision-making process for Risk Reduction (RR). Statistical descriptions including maximum, minimum, average, median, most likely, and standard deviation, are one of good means of addressing uncertainties when measuring values of parameters. Examples of such parameters are aquifer flow rate and direction, precipitation, porosity of geological material, hydraulic gradient, dilution of leachate hazards. The statistical based approach has been employed to an extent in the development of the RAM computer model discussed in the following Chapter.

5.9 Risk Characterisation (R Cha)

Risk from a hazard is the measure of likelihood or degree of possibility (or probability / chance) that the hazard will cause harm in actual circumstances of use whereas anything that has a potential to cause harm(s) is referred to as a hazard (adapted from EHSC, 2002; HSE, 1996b; 2003; EPA, 2004c). In an equation risk can be expressed like this (Environment Agency 1996; 2003e):

$$\text{Risk} = (\text{Chance}) \times (\text{Outcome}) \qquad (5.2)$$

or (Jaggy, 1996):

$$\text{Risk} = (\text{Probability of an undesired event}) \text{ x } (\text{Impact of the event}) \qquad (5.3)$$

In above expressions, this is worth noting that chance or probability form quantitative part of risk where as outcome or impact does the qualitative factor. This implication is further explained below in Sections 5.9.1, 5.9.2 and 5.9.3 regarding Hazard Index, Carcinogenic Risk and Non-carcinogenic Risk, respectively.

The Risk Characterisation sub-part is the final step in the RA framework. In the R Cha the assessments of exposures and hazard concentrations carried out in the HA process, are summarised and integrated into quantitative and qualitative expressions of risk. Major assumptions, scientific judgements, and to the extent possible, estimates of the uncertainties embodied (in various modules and sub-modules of the RA process) can also be highlighted in this sub-part (EPA, 1989). In the RA framework, the R Cha is divided into three modules as described below and illustrated in Figure 5.1 (EPA, 2000b).

5.9.1 Hazard Index / Hazard Indices (HI)

For a given set of hazard, pathway and receptor or target, Hazard Index (HI) is the comparison of Target Concentration Final (TCf) with Critical Concentration (Cri C). Mathematically, it is the ratio of these two parameters, presented like this:

$$HI = TCf \,/\, Cri\ C \qquad (5.4)$$

Generally HI is the ratio of the target intake concentration to critical concentration (Molak, 1997; CIRIA, 2001). Nevertheless, in this research study, as explained earlier in Section 5.5, TCf is compared with Cri C rather than just target intake concentration in order to account for hazard concentration already or initially present in the receptor boundaries, if appropriate. The consideration of maximum TCf value to calculate HI ratio for a given set of hazard, pathway and receptor will result in the maximum value of HI and thus indication of the risk potential for a worst case scenario. On the other hand, using the mean or most likely TCf value will render the most likely HI value corresponding to the most likely risk scenario. Similarly, the application of the minimum TCf value will yield the minimum HI figure representing least bad risk scenario (further details in Section 6.9 of Chapter 6). Thus there can be three streams of HI values, in order to correspondingly reflect on most likely, worst case and least bad scenarios of risk for each combination of the hazard, receptor / target and pathway for a given landfill.

In this module no discrimination is made between carcinogenic and non-carcinogenic hazards. HI is calculated for them all. However, if a given target is, for example, a human or mammal for which carcinogenic and non-carcinogenic classification makes sense, the other two modules of Risk Characterisation below can be considered. However, if a given target is, for instance, a river or an aquifer then carcinogenic and non-carcinogenic classification is of no significance as a river or an aquifer can not catch cancer, and thus the other two modules will be of no significance to consider in such a scenario. However, if a given target is a human or mammal, although the other two modules below will be considered, but still this module can be useful as a preliminary stage to see what is the order of HI values corresponding to various hazards both carcinogenic as well as non-carcinogenic. However, in case of carcinogenic hazards, HI would be the comparison between TCf and Cri C in which Cri C would be corresponding to acceptable risk level such as one in a million (Fischhoff, 1994; Finlayson et. al. 2004; Washburn, 2005). For non-carcinogenic hazards HI would also be the ratio between TCf and Cri C but the Cri C is generally Reference Dose (RfD). This concept is elaborated further in the other two modules of Risk Characterisation below.

Once values of all hazards HI values have been worked out, then a risk assessor can pinpoint the ones which are greater than unity as those hazards would be the ones with concentrations beyond safe levels. In other words, if the HI value is more than unity for a given hazard then it is deemed that there is a potential risk for the unwanted outcome or adverse affect to occur. If HI is less than unity then it is unlikely that the unwanted event or adverse affect will occur. As a general rule, the higher the HI value than unity the more the risk for the unwanted or adverse affect to happen. For a receptor such as a river, if the HI value is more than unity for a hazard (no matter carcinogenic or non-carcinogenic) then there is a risk that river will become polluted by that hazard and vice versa. With reference to the risk definition above, the HI value is the quantitative part of the risk expression and the river becoming polluted or not polluted is the qualitative aspect of the risk. Whereas if a given receptor is, for example, a human then the HI more than unity for a carcinogenic hazard would mean that there is a risk of one in million to suffer cancer (if one in a million is the acceptable level) and vice versa, provided the dose-response relationship is linear. In this case again, HI is the quantitative factor of the risk expression and catching cancer or not is qualitative facet. In the case of a non-carcinogenic hazard and human as a receptor, an HI value greater than unity would imply that there is a risk for adverse affect such as headache to occur and vice versa. Also in this case, HI is the quantitative portion of the risk and catching a headache or not is qualitative side of the risk.

The *total hazard index* (THI) for all hazards for a given set of pathway and target is calculated by adding all the individual Hazard Indices as presented in the mathematical expression below (CIRIA, 2001; EPA 1989). Similarly, THI can be worked out for all hazards for all sets of pathways and targets in a given scenario, and then all can be aggregated together to estimate an over all Hazard Index. For this, the RAM (or model described in Chapter 6) would have to be iterated as many times as the sets of pathways and receptors. However, if the aggregated value, THI, is less than unity then it implies that there is no single hazard overstepping safe levels of risks. If the THI is greater than unity then a risk assessor has to make sure with all hazards on individual basis if there is any individual Hazard Index greater than unity.

$$THI = \sum_{i=1}^{l} TCf_i \,/\, Cri\ C_I \qquad (5.5)$$

Where, THI = Total Hazard Index

TCf_i = Receptor or Target Concentration Final (or Intake Concentration / dose if the target background concentration is negligible or zero) for i^{th} hazard / contaminant for a given set of pathway and target (mg/kg/day)

Cir C_i = Critical Concentration for i^{th} hazard / contaminant for the given set of pathway and target (mg/kg/day)

l = Total number of hazards for a described scenario

5.9.2 Carcinogenic Risk

With respect to the definition of risk above, a carcinogenic risk can be stated as the probability or chance of a receptor / target to develop cancer over a given time scale. For carcinogens, risks are estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to a potential carcinogen (EPA, 1989). Unlike non-carcinogens, carcinogens are considered 'non-threshold'.

The Unit Cancer Risk (UCR), which also used to be called Potency Factor (PF) or Slope Factor (SF), converts estimated daily dose intakes averaged over lifetime of exposure directly to incremental risk of an individual developing cancer (EPA, 2004b). UCR is the reciprocal of the concentration of a carcinogen measured in milligrams per kilogram of animal body or human body weight per day. Mathematically it is expressed as $1/(mg\ kg^{-1}\ day^{-1}) = mg^{-1}\ kg\ day$. It can also be defined as the risk produced by a life time average daily dose of 1 $mg\ kg^{-1}\ day^{-1}$. Because relatively low intakes (compared to those experienced by test animals) are most likely from environmental exposures, it generally can be assumed that the dose-response relationship will be linear in the low-dose portion of dose-response curve. Under this assumption, the UCR is a constant and risk will be directly related to intake. Thus, the linear form of the carcinogenic risk equation is usually applicable for estimating carcinogenic risks (Pepper et. al., 1996; EPA, 1989; Axelrad et. al., 2005). The linear low-dose equation is described below (Molak, 1997; EPA, 1989). There are many mathematical models available to chose from, including the multistage model, the linear multistage model, the one-hit model, the multi-hit model, and the probit model. It is up to a risk assessor which model information they want to use. It is highly recommended that a toxicologist should be consulted not only for the selection of a model but also for working out critical concentrations of given hazards in terms of both carcinogenic and non-carcinogenic hazards.

$$R = TCf \times UCR \qquad (5.6)$$

Where, R = Carcinogenic risk is the probability of an individual developing cancer over given time period. For instance, one in a million, 3 in a million. Mathematically these examples can be expressed as 1×10^{-5}, 3×10^{-5}, respectively. Risk is a dimensionless parameter and thus has no unit.

TCf = Final concentration of carcinogen in a target boundaries. TCf would be Intake Dose or Concentration if initial carcinogen concentration in the target is negligibly zero. Generally this would be chronic daily intake averaged over 70 years. The unit of TCf is mg/kg/day

UCR = Unit Cancer Risk $(mg/kg/day)^{-1}$ for a given carcinogenic hazard. In other words, it is the reciprocal of the Critical Concentration (Cri C) of a given carcinogen as the unit of Cri C is mg/kg/day.

It is necessary to assess potential health affects of more than one carcinogenic hazard / chemical substance. Estimating risk or hazard potential by considering only one hazard at a time might significantly underestimate the risks associated with simultaneous exposures to several hazards / chemicals. The *total risk* (TR) for all carcinogenic hazards for a given set of a pathway and target is calculated by adding all the individual risks quantified for all the carcinogenic hazards where this TR obviously should not exceed unity (CIRIA, 2001; EPA 1989). This is mathematically expressed in the form of an equation below. Similarly, TR can be worked for all carcinogenic hazards for all sets of pathways and targets in a given scenario, and then all can be aggregated together to estimate an over all carcinogenic risk, for which the RAM (or model described in Chapter 6) would have to be iterated as many times as the sets of pathways and receptors. The use of maximum, most likely / mean and minimum TCf values would correspondingly yield worst case, most likely and least bad risk scenarios, respectively, for each set of hazard, pathway and receptor.

Unlike non-carcinogens, risk assessment emphasises on the overall aspect of carcinogenic risk (Washburn, 2005). For instance, if there is a risk of 1 in a million for catching lung cancer and there is risk of 1 in million for developing liver cancer, then over all risk of cancer would be 2 in a million, irrespective of what organs develop cancer. Thus, for carcinogen risk aggregation RA is not 'organ-specific', where as for non-carcinogens RA is generally organ-specific.

$$TR = \sum_{i=1}^{l} TCf_i \times UCR_I \tag{5.7}$$

Where, TR = Total Risk from all carcinogenic hazards in a given scenario

TCf_i = Final Hazard Concentration (or Intake Concentration or Dose if the target background concentration is negligible or zero) for i^{th} carcinogenic hazard for a given set of pathway and target (mg/kg/day)

UCR_i = Unit Cancer Risk (or reciprocal of Critical Concentration i.e. Cri C) for i^{th} carcinogenic hazard for the given set of pathway and target $(mg/kg/day)^{-1}$

l = Total number of hazards for a described scenario

5.9.3 Non-carcinogenic Risk

With respect to the definition of risk above, a non-carcinogenic risk can be stated as the likelihood or chance of a receptor / target to suffer a non-cancer adverse health affect (such as skin infection, headache) over a given time scale. Unlike carcinogens, in the case of non-carcinogenic responses, the assumption is that some threshold exists below which there is no toxic response, that is, no adverse affects will occur below some very low dose. In other words, dose-response effects for non-carcinogens allow for the existence of thresholds, that is, a certain quantity of a non- carcinogenic substance or dose below which there is No Observed Adverse Effect Level (NOAEL) by virtue of the body's natural repair and detoxifying capacity. These thresholds are represented by the Reference Dose (RfD), of a substance, which is the intake or dose of the substance per unit body weight per day (mg kg^{-1} day^{-1}) that is likely to pose no appreciable risk to human populations, including such sensitive groups as children (Pepper et. al., 1996; EPA, 2004b).

Non-carcinogenic risk is indicated by means of Hazard Index (HI) as already discussed in Section 5.9.1 above and so is the THI aggregation aspect. However, Cri C for non-carcinogens can be used for quantitative risk assessments also in the following way:

$$\text{Risk} = \text{PF}\,(\text{TCf} - \text{Cri C}) \qquad (5.8)$$

Where PF is the potency factor of the slope of the dose-response curve, TCf is final target concentration and would effectively be daily intake dose if initial or background target concentration is zero, and Cri C is RfD indeed. The maximum, most likely / mean and minimum TCf values for a given set of hazard, pathway and target would result in three sets of risk scenarios which are worst case, most likely and least bad, respectively (explained further in Chapter 6). However, if the above non-carcinogenic risk expression is applied for non-carcinogenic hazards then the total (non-carcinogenic) risk can be calculated just like using the above TR expression (i.e. Equation 5.7) but still in the format of Equation 5.8 not 5.6. This is because Equation 5.6 is specifically for carcinogens and Equation 5.8 is for non-carcinogens. If such an aggregation approach is applied to non-carcinogenic scenarios, then all non-carcinogenic affects need not to be discreetly considered at individual level. Moreover, like a risk of any kind of cancer in any organ is added with the risk of cancer in any other organs irrespective of type of cancer, carcinogen and organ affected. Similarly, the risk of any non-carcinogenic affect from any non-carcinogen on an organ can be summed up with other risks of non-carcinogenic affects from non-carcinogens on any other organs. However, in general, the Hazard Index approach, that is the ratio of TCf and Cri C is used as an indicator of risk potential from non-carcinogens rather than the risk expression given above (Pepper et. al., 1996; Washburn, 2005).

5.10 Risk Reduction (RR)

This is the second main part of Risk Management (RM) as shown in Figures 5.1 (and Figure 2.2, Chapter 2). This part comprises a number of sections such as Risk Evaluation (R Eva), Risk Control (R Cntrl), Consequences Evaluation (Conse Eva), Costs Evaluation (Costs Eva), Risk Monitoring (R Monit), Corrective Action. In the R Eva, consequences of risks or losses due to risks are evaluated considering if the hazards do successfully cause the potential harm. For instances:

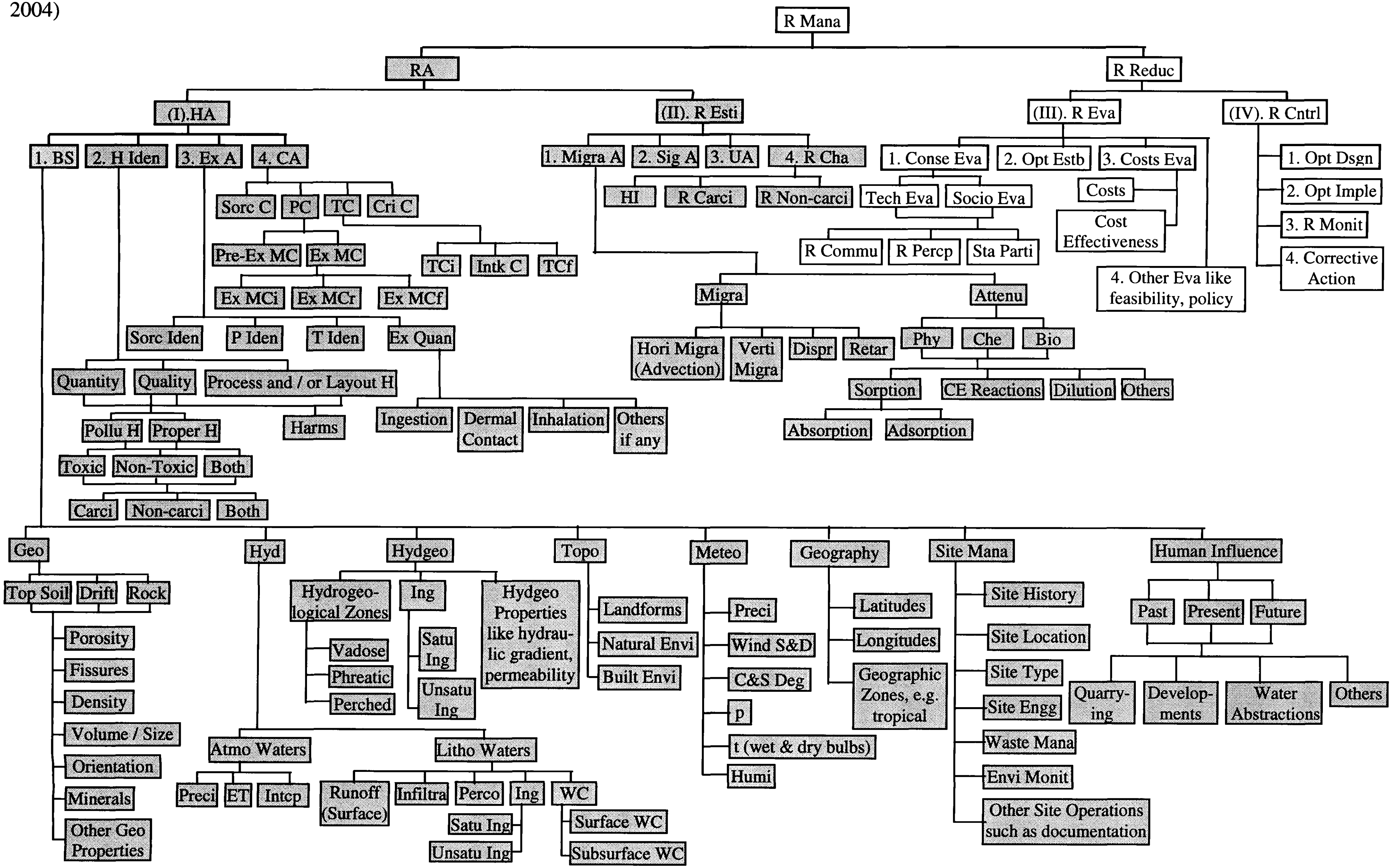
- If a given hazard / contaminant hits a surface water course (such as a lake) and kills a number of certain aquatic species then what will be the effects on the ecosystem of the region?

- If a given hazard pollutes the groundwater sourcing a woodland or farms land then what impacts will there be on the local economy?

Risk evaluation is concerned with determining the sensitivity of the estimated risks for those affected, therefore it includes the element of Risk Perception (DoE, 1990). This is where the sociological factors are involved in risk assessment as Risk Perception is the overall view of risk held by a person or group of people and includes both feeling and judgement (DoE, 1990). However, Technical Evaluation is to be there also side by side with the sociological evaluation (Figure 5.1).

The R Eva is to assist a risk assessor to prioritise the hazards and risks in terms of their significance and ultimately contributes in prioritising the options of Risk Control. Then, the cost analysis of those options can be carried out to assess their cost-effectiveness on individual basis, thereby, further prioritising the matter in the light of 'sustainable development' philosophy. However, all such aspects are covered in the Risk Reduction part, which is not the focus of this research study. Therefore no further details on the RR are described in this document.

Figure 5.1: The Holistic Framework of the Risk Assessment and Management – Shaded boxes are in the RA's remit (Adapted and derived from the work of various authors e.g. Peacock and Whyte, 1992; Tweeds, 1996; IWM, 2000; EPA, 2000b; CIRIA, 2001; Viswanathan et. al., 2002; Boguski, 2004; BJAAM, 2004)

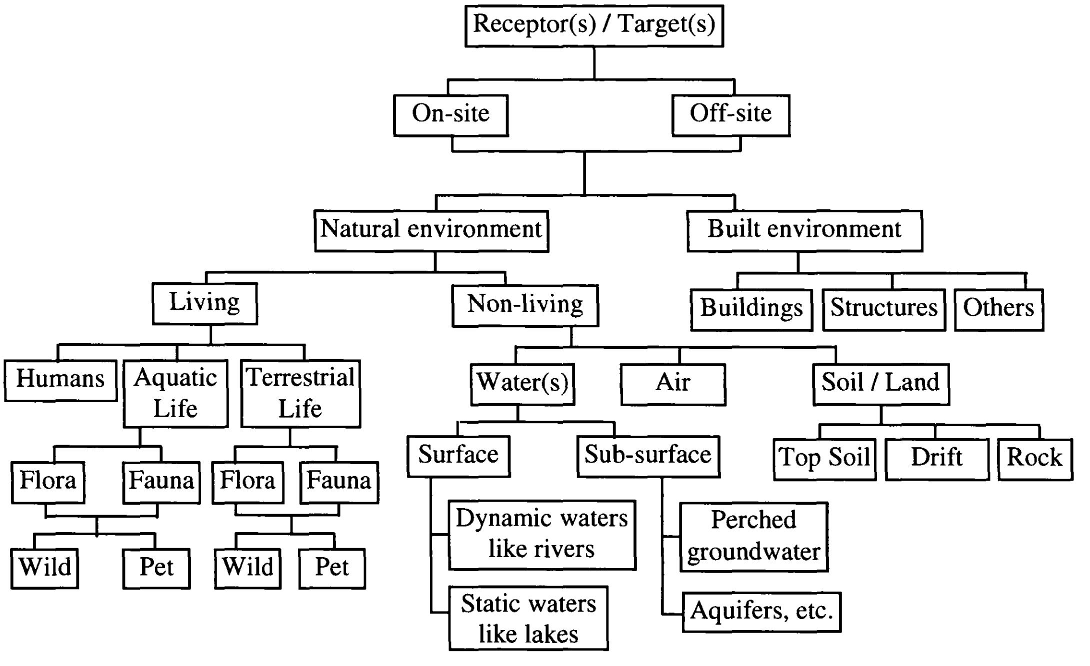


Notation:

A	Assessment	Mana	Management
Atmo	Atmosphere or Atmospheric	MC	Medium Concentration
Atmo Waters	Atmospheric Waters	Meteo	Meteorology / Climate
Attenu	Attenuation	Migra A	Migration Assessment (of pollutants)
B	Baseline / preliminary	Monit	Monitoring or Monitor
Bio	Biological	Natural Envi	Natural Environment
BS	Baseline Study	Non-carci	Non-carcinogen(s) / Non-carcinogenic
Built Envi	Built Environment	Opt	Option(s)
C	Concentration	Opt Dsgn	Options Design
C&S Degree	Degree of Cloudiness and Sunlight	Opt Estb	Options Establishment
Carci	Carcinogen(s) / Carcinogenic	P	Pathway
CA	Concentration Assessment	p	Pressure
CE	Cation Exchange	P Iden	Pathway Identification & Categorisation
Cha	Characterisation / Characterise	Parti	Participation or Participate
Che	Chemical	PC	Pathway Concentration
Cntrl	Control	Perco	Percolation
Conta	Contaminants	Phy	Physical
Conse	Consequence(s)	Pre-Ex MC	Pre-Exposure Medium Concentration
Conse Eva	Consequence(s) Evaluation	Preci	Precipitation
Costs Eva	Costs Evaluation	Proper	Properties
Cri	Critical	Quan	Quantification
Cri C	Critical Concentration	R	Risk
Dispr	Dispersion	R Cha	Risk Characterisation / Characterise
Dil C	Dilution Concentration	R Cntrl	Risk Control
Engg	Engineering	R Commu	Risk Communication
Envi	Environment	R Esti	Risk Estimation
Envi Monit	Environmental Monitoring	R Eva	Risk Evaluation
Estb	Establishment	R Mana	Risk Management
Esti	Estimation	R Monit	Risk Monitoring
ET	Evapo-transpiration	R Percp	Risk Perception
Eva	Evaluation(s)	R Reduc	Risk Reduction
EWEQ	Existing Waters Existing Qualities	RA	Risk Assessment
Ex	Exposure	Retar	Retardation
Ex A	Exposure Assessment	Satu Ing	Saturated Ingress/Phreatic or GW Ingress
Ex MC	Exposure Medium Concentration	Site Engg	Site Engineering
Ex MCi	Initial Ex MC	Site Mana	Site Management
Ex MCr	Reaching Ex MC	Socio	Sociological or Sociology
Ex MCf	Final Ex MC	Socio Eva	Sociological Evaluation
Ex Quan	Exposure Quantification	Sorc	Source
Geo	Geology	Sorc C	Source Concentration
GW	Ground Water	Sorc Iden	Source Identification & Categorisation
H	Hazard	Sta	Stakeholder(s) and public
H Iden	Hazard Identification	Sta Parti	Stakeholder(s) & Public Participation
HA	Hazard Assessment	Sub-surface WC	Subsurface Water Course(s)
HI	Hazard Index or Indices	Surface WC	Surface Water Course(s)
Hori Migra	Horizontal Migration	t	Temperature
Humi	Humidity and / or Relative	T	Receptor / Target

	Humidity		
Hyd	Hydrology	T Iden	Target Identification & Categorisation
Hydgeo	Hydrogeology	TC	Target Concentration
Iden	Identification & Categorisation	TCi	Initial / Background Target Concentration
Infiltra	Infiltration	TCr	Reaching Target Concentration
Ing	Ingress	Tech Eva	Technical Evaluation
Intcp	Interception (Loss)	Topo	Topography
Inter	Intermediate	U	Uncertainty or Uncertainties
Inter MC	Intermediate Medium Concentration	UA	Uncertainty Assessment
Intk	Intake	Unsatu Ing	Unsaturated Ingress/Vadoze Water Ingress
Intk C	Intake Concentration	Verti Migra	Vertical Migration
Leach	Leachate	W	Water
Litho	Lithosphere or Lithospheric	Waste Mana	Waste Management
Litho Waters	Lithospheric Waters	WC	Water Course(s)
M	Medium or Media	Wind S&D	Wind Speed and Direction

Figure 5.2: Classification of Receptors / Targets



Note:
The word 'Pet' stands for species such as animals in a zoo, fish in a human-made pond, crops, a lawn or garden in a built environment, or may be even artificial forests. Thus artificial forests, lawns or gardens in a built environment are to be covered in the Pet-Flora category rather than under Built Environment class of receptors / targets. However, it is still up to the choice of a risk assessor, if they decide otherwise in a given hazard and risk assessment scenario.

Chapter 6

THE COMPUTATIONAL DEVELOPMENT OF THE METHODOLOGY

In this chapter the Risk Assessment Methodology (RAM), developed in the previous chapter, is translated into a computer model. In this computational form of the RAM, however, all the modules and sub-modules are not to be developed to their full potential (as stated earlier in Section 2.4 of Chapter 2). However, the RAM model draws on all the factors related to risk assessment in order to be tied together in an algorithmic fashion. All the elements are linked together via various 'e-buttons' wherever necessary and appropriate to facilitate the programme user in terms of mutual data and / or information transfer and access. Due to brevity, not all but some of the forms from the model are depicted in this chapter to explain how the model operates. However, for more details on various forms, the RAM model needs to be run on a computer. The chapter also discusses which computer master programme has been selected and why, in order to prepare the RAM model.

6.1 Preamble

6.1.1 Background

In the light of the issues raised in Chapters 3 and 4, it is likely that there is a requirement not only for a quantitative hazard and risk assessment methodology for landfills with a holistic approach, but also for an electronic representation of this methodology in the form of a computer model that is more readily useable than simply a documented procedure. In other words, risk assessment practitioners require a knowledge-base computer model of this procedure, which is more advanced, yet practical and will help satisfy current and future requirements. The underlying context of the model development was decided, based upon the needs of a risk assessment system specifically for landfill leachate (Chapters 1, 2, 3 and 4). This computer model development, due to its algorithmic and user-friendly format, also encompasses a wide domain of relevant users and subjects such as, legislation, engineers, risk assessors, risk managers, lenders, funders, and contractors. Using information derived from literature (such as Cox and Dudley, 1997; Dowling, 1998; ZDNet, 1998), anecdotal exchanges with experts and end users, and personal intuition, an awareness of possible avenues for model development was cultivated. On the basis of the material gathered, it was decided that the model development option should involve the formulation of a knowledge-base model which may find practical acceptance within industry, consultancy services and the public sector (Butt and Oduyemi, 2003).

6.1.2 The fundamental model conception and limitations

After reviewing various computer languages and master programmes for use as a platform for developing the computer model and after discussing different approaches with computer experts, Microsoft Access was selected. This decision was based upon various important factors, examples of which are as follows (Powell, 1993; Litwin, 1995; Prague, 1995; Coles and Rowley, 1996; 1997a; 1997b; ZDNet, 1998; Hasanain, 1999; Butt and Oduyemi, 2003):

- MS Access is comparatively easy and quick to learn, which makes it particularly good for beginners and non-technical users (Cassel, 1994; Gaylord, 1995);
- Visual Basic for Applications (VBA) is embedded within it;
- It is a relational database product; and
- In summary, it is a very powerful tool and yet, it is not simply a database programme rather a Database Management System (DBMS).

Having established a basic development of templates, the issues of input and output data were addressed. Typically, a knowledge-base model requires and generates a significant amount of data. Given that the input datasets for this type of model are often complex, incomplete and sometime inaccessible, a decision was taken to adopt a policy of alternative provisions of data. The objective was to enable risk assessors to make use of 'representative' types of data from literature, databases or from other alternative means, such as information from relevant experts based on their expertise and experience when site-specific data are not enough (Butt and Oduyemi, 2003).

The RAM model presented is independent of the types of wastes (hazardous or non-hazardous) that are buried in a given landfill and can take into account any pollutants. In other words, the model can accommodate any pollutants irrespective of whether they come directly from buried wastes or as a result of any chemical, physical and / or bio-chemical waste degradation process. The model does not consider unlimited scenarios of waste degradations, but the resultant pollutants only. Moreover, the model itself does not consider chemical, physical and / or bio-chemical attenuation of leachate. It is up to risk assessors to decide how they want this issue to be addressed, for example, by using the LandSim model (Environment Agency, 1996; 2001; 2003e) or HELP software (Landcare Research, 2003; Scientific Software Group, 1998). However, this model is designed in a manner that allows a risk assessor to perform work outside the model in order to take account of aspects such as waste degradation and leachate attenuation processes and then feed back to the model the results from the external process. The computer-aided tool is flexible also in the sense of method selection. For instance, some methods are suggested within the model regarding leachate quantity estimation. Adopting these methods is not mandatory, as the user can apply either any of these suggested methods or any other method outside the model and then put the estimated values back into the model. Similarly, the model is not to dictate pathways or media. This could be an aquifer, perched groundwater or any other media. The same flexibility applies even from the perspective of environmental receptors.

Uncertainties that may be involved in estimating or measuring values of parameters (such as surface water runoff, groundwater ingress) should be accounted for to the best of the user's ability. The scope of the work presented in this research does not consider such uncertainties in detail due to the following reasons. These include:

- there are various methods that can be used to estimate or measure a given parameter, such as interception, evaporation;

- the number of possible scenarios is unlimited, for instance, variation in nature of receptors / targets even within the same category like variation from one human to another;
- above all the focus of the model development is the electronic presentation of the holistic Hazard and Risk Assessment Methodology rather than the details of, for example, estimation of uncertainties (for each and every scenario).

Nevertheless, general uncertainties (listed in Section 5.8 of Chapter 5) that may be involved in a method being applied by a risk assessor have been described to be accessible as a general guideline in the Uncertainty Assessment section of the model. Further details on this are set out in Section 6.8 of this chapter. However, to an extent, the element of uncertainties has been dealt with in the model. This has been done both spatially and temporally by applying a statistical approach of maximum, mean / most likely and minimum. Further details and examples on this are described in the sections below which discuss various modules and sub-modules of the model.

It is worth mentioning that one of the major issues with landfill risk assessment and modelling is timeframe – how long would be taken from the time of placement of waste in landfill to the time when, for example, concentrations of the pollutants in the groundwater may be highest at the point of exposure. In some cases, this time duration could be in the order of tens of years and sometimes as many as hundreds of years depending on characteristics of a given landfill scenario (Washburn, 2005). Therefore, the process of risk analysis can be and should be performed for different 'age scenarios' of a given landfill, for instance 10 years duration, 30 years time, 50 years and even 70 years which is generally an average human generation length as considered in carcinogenic risk assessments (EPA, 1989; Asante – Duah, 1993; 1996; CIRIA, 2001). So in order to account for various scenarios due to temporal variations in landfill systems a number of iterations of the RAM model may be needed.

6.1.3 The template of the knowledge base

The computer version of the methodology is, in effect, a template (Ingles, 2003; Butt et.

al., 2006b). This template, which in fact is a knowledge-base computer model, is essentially an electronic translation or representation of the methodology. The term 'knowledge-base' implies structured knowledge (Boyle and Baetz, 1997; 1998). This template is not only a structured knowledge but also contains databases. For instance, List 1 and List 2 substances / pollutants from the Groundwater Directive have been included in the computer programme as a database, which a risk assessor can utilise, particularly if the groundwater, or a drinking water course is a potential receptor. However, the databases, which are embedded in the knowledge-base model, are not fixed or mandatory and have an in-built flexibility as a risk assessor can override them. For instance, referring to the above example again, a risk assessor can ignore or adapt the pollutants that have already been fed into the computer model as a default database. This ensures that the adapted database used by the model reflects the characteristics of a given or specific landfill scenario. The tool also allows the landfill assessor to explain their reasoning for the addition, or subtraction of certain pollutants, providing an important validation and checking facility. For this purpose, there are 'Specific Description' forms provided in the model for various modules and sub-modules of the methodology. These forms can be used for site-specific justifications when a default database is adapted in the programme. The location of these forms in the model and other further details on these forms are described in Sections 6.2, 6.3, 6.4, 6.5 and 6.9 of this chapter where these modules and sub-modules are discussed as individuals. Similarly, if a risk assessor uses certain methods (especially other than those already exist within the tool's database) to estimate / measure a parameter, they can use these 'Specific Description' forms to state the corresponding justifications and details. For instance, there is a database of methods contained in the model to estimate leachate quantity. If a landfill assessor decides to or not to use any of these methods from the default database but some other methods, the assessor can describe relevant reasons in the corresponding 'Specific Description' form (Butt et. al., 2006a; 2006b).

6.1.4 The format and functions of the model

When the RAM computer model is run, the first dialogue box that will appear on the monitor / screen is shown in Figure 6.1. The click on the button 'Start the Model' leads to pop open another box (Figure 6.2), which is the main front page of the model in order to provide links to all modules and sub-modules related to the RAM model. The 'Close' button in Figure 6.1 is to turn the model off when desired. In Figure 6.2, the main front page of the model, in fact, depicts the structure of the Risk Management, which comprises two sections. These sections are Risk Assessment and Risk Reduction. The former is the focus of this research study and not the latter. Therefore in the main front page (Figure 6.2), the links under the umbrella of Risk Assessment section are hyperactive in order to let users access risk analysis related modules (and subsequent sub-modules). The buttons associated with the Risk Reduction part of the Risk Management are not hyperactive as they do not constitute the RAM or the remit of this research work.

The overall framework of the Risk Assessment section in the model is developed in the same style as the Risk Assessment Methodology (RAM) itself as explained earlier in Section 5.1 of Chapter 5. That is, the Risk Assessment section of the model (See Figure 6.2) is developed into two main parts. These are Hazard Assessment (HA) and Risk Estimation (R Esti), and each of these parts consists of four sub-parts. A click on the button 'Hazard Assessment (HA)' will open a form shown in Figure 6.3. On this form, four links are laid down for the four sub-parts of HA. These links are Baseline Study (BS), Hazard Identification and Categorisation (H Iden), Exposure Assessment (Ex A) and Concentration Assessment (CA). These buttons, when clicked, will open up corresponding panes of BS, H Iden, Ex A and CA, respectively. The button 'What is HA?' is to open a form as a quick reference for users to learn about HA and its sub-parts. This form is not shown here but can be retrieved in the model when in use. And the link 'Back' is to close the HA form. These four HA sub-parts can also be accessed via the four corresponding links provided directly below 'Hazard Assessment (HA)' button shown in Figure 6.2. Like the case of HA, the button 'Risk Estimation (R Esti)' in Figure 6.2 is to open the form shown in Figure 6.4. This form contains four links for the four sub-parts of R Esti, which are Migration Assessment (Migra A), Significance Assessment (Sig A), Uncertainty Assessment (UA) and Risk Characterisation (R Cha). These buttons when pressed, will pop open corresponding panes of Migra A, Sig A, UA and R Cha, respectively. The button 'What is R Esti?' is to open a form, which explains

R Esit and its sub-parts. This form is not shown here but is accessible in the model when in use. And the link 'Back' is to close the R Esti form. These four R Esti sub-parts can also be accessed via the four corresponding links laid down directly below 'Risk Estimation (R Esti)' button shown in Figure 6.2. The R Cha button further branches into three sub-links that are explained in Section 6.9 of this chapter.

Given the variations in nature, size and function of various factors of the methodology, the format of all modules, sub-modules and parameters of the model have been developed in a similar pattern to the possible best degree in order to render the model smoothly and conveniently useable by the users. Furthermore, the idea is to ease not only the mutual information transfer between modules and sub-modules but also the traceability or tractability of any module, sub-module, parameter, information and data in the structure of the methodology model. Also, where appropriate, the mutual data and / or information transfer amongst the modules and sub-modules of the RAM model is designed to take place automatically. Further descriptions on the format and functions of the model are contained below in Sections 6.3 through to 6.9, where modules and sub-modules of the model are individually dealt with.

Figure 6.1: The First Page of the RAM Computer Model

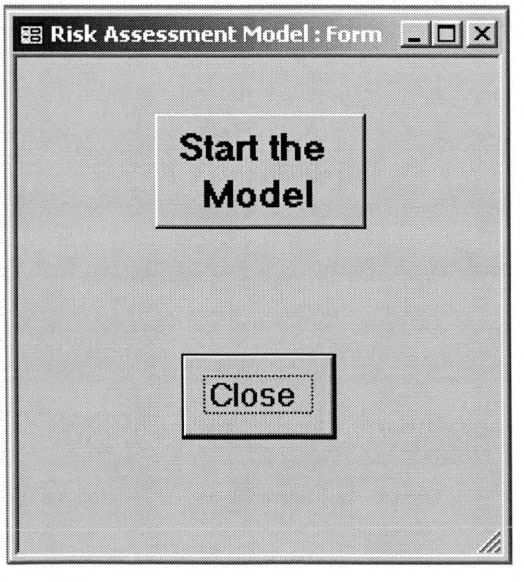


Figure 6.2: The Main Front Page or Form of the RAM Computer Model

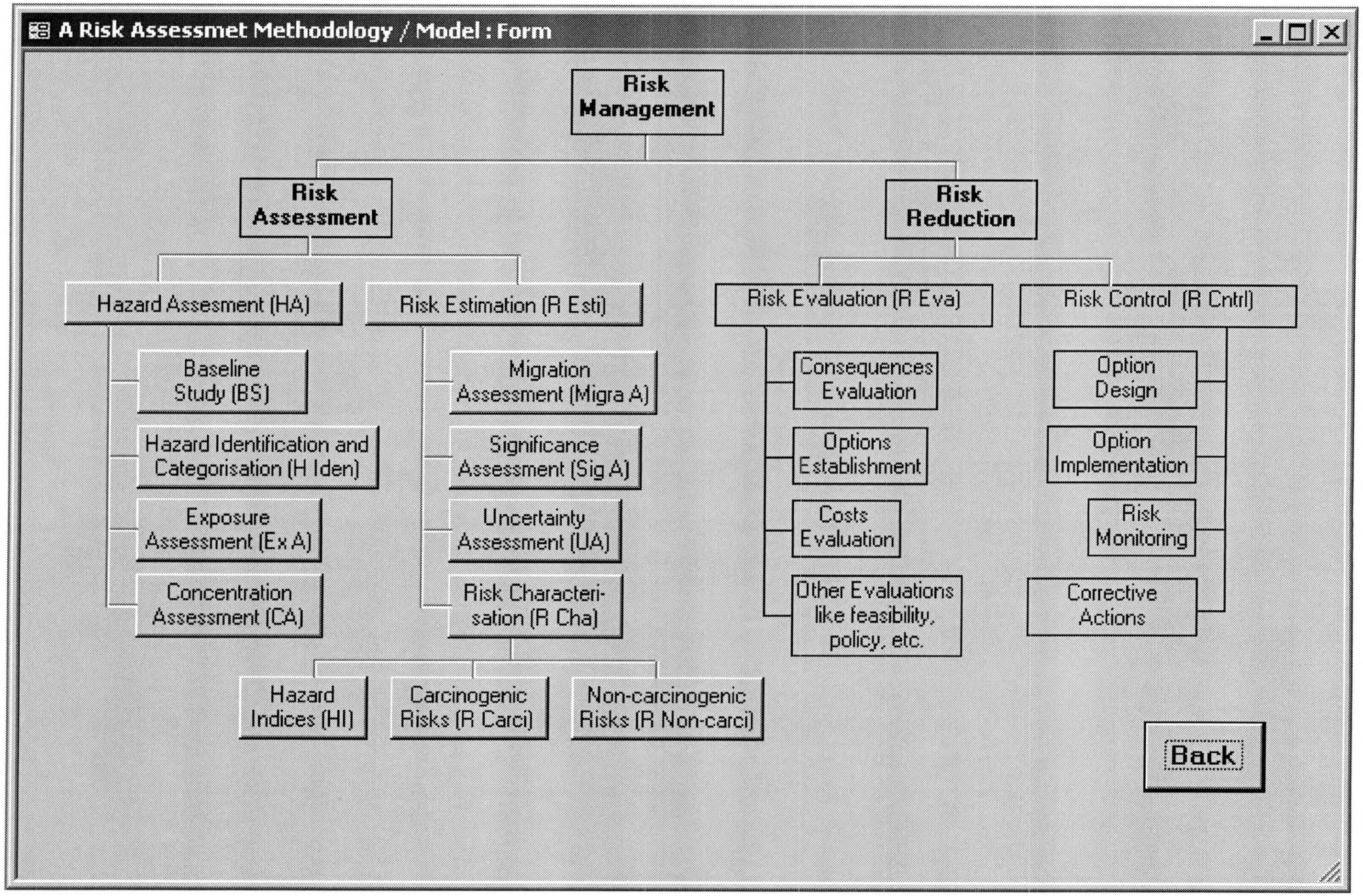


Figure 6.3: The Hazard Assessment (HA) Form in the RAM Model

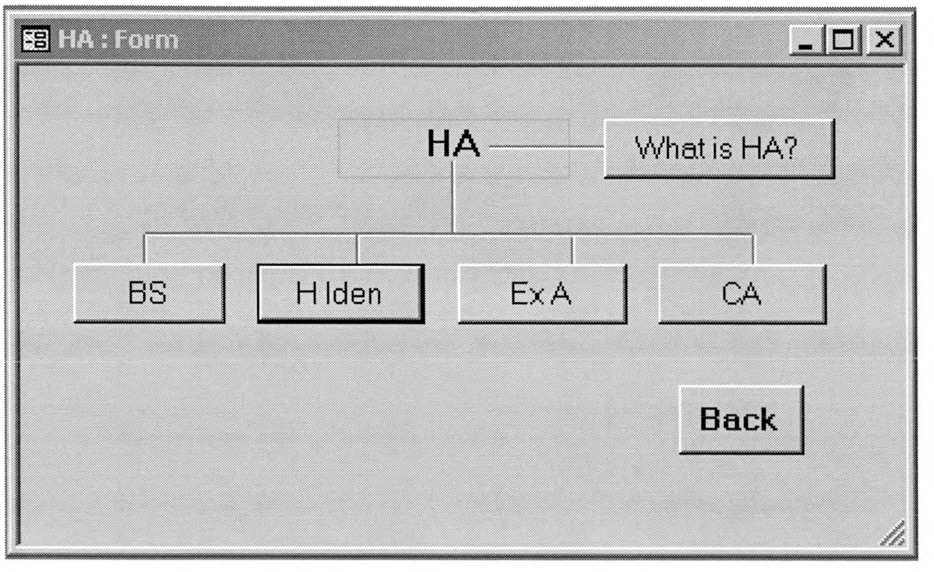
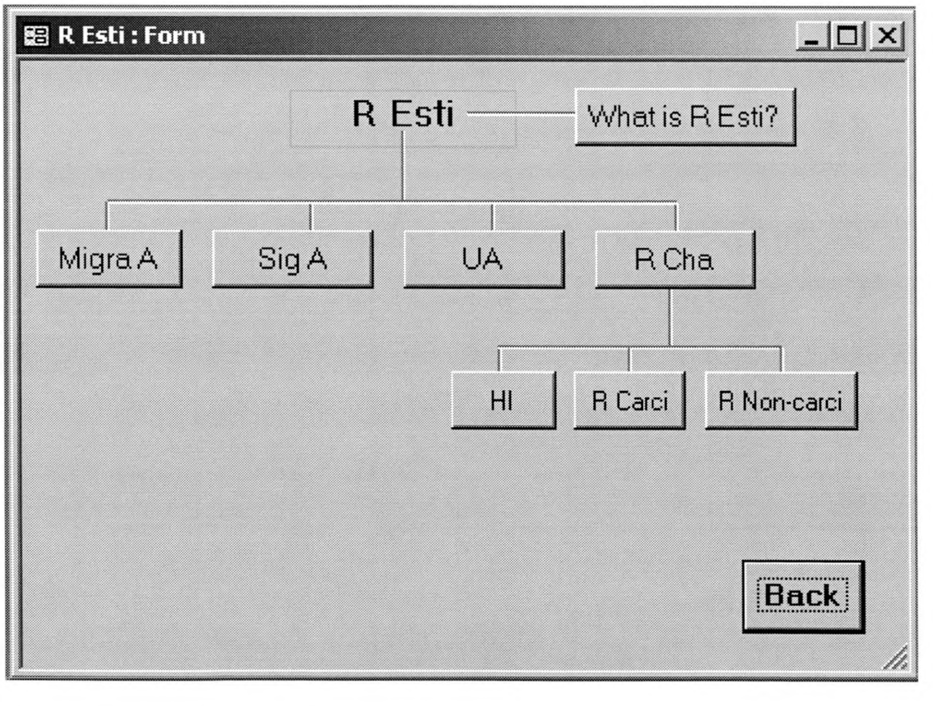


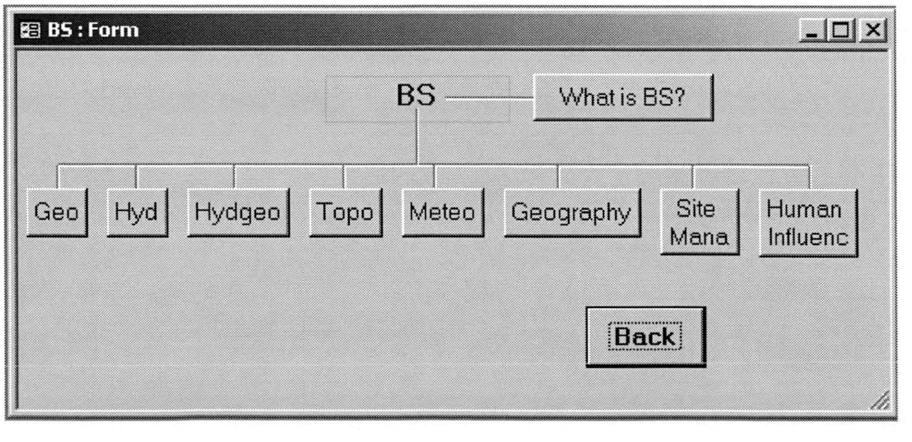
Figure 6.4: The Risk Estimation (R Esti) Form in the RAM Model



6.2 Baseline Study (BS)

When the button 'Baseline Study (BS)' on the main front page (shown in Figure 6.2) is pressed, a form as depicted in Figure 6.5 will open. This form possesses links to all the eight modules of the BS. The model user can put all the relevant data and information in these eight modules for use in the later stages of the risk assessment process. These eight modules have a similar format. However, given the scope of this research study, only the hydrology module has been developed to great detail and the other seven are briefly covered thereby leaving the potential for further development in future research in the same style as the Hydrology module. These seven modules are prepared to a limited extent in the shape of each possessing a 'General Description' form and a 'Specific Description' form. The former explains and provides a general guideline for what sort of data / information are to be gathered in the module. Whereas the latter is to provide room to the user to describe site specific information / data on the module. These forms can be seen in the model when in use and are not shown in here due to brevity. However, the development of the Hydrology module is explained below in more detail. The 'What is BS?' button in Figure 6.5 is to access a form which describes BS and all its eight modules briefly for quick reference for the model user. The 'Back' button will take the user back to the main front page of the model (Figure 6.2) thereby closing down the BS form.

Figure 6.5: The Baseline Study (BS) Form in the RAM Model



In Figure 6.5, clicking the link 'Hyd' (an abbreviation for Hydrology) the user can access the forms shown in Figures 6.6 and 6.7. The former is to deal with parameters which concern the atmospheric waters including precipitation, interceptions and evaporation, transpiration (or both i.e. evapo-transpiration). The latter covers parameters which are related to lithospheric waters comprising (surface) runoff, infiltration, percolation, ingress (either or both saturated and unsaturated waters below earth surface), water courses (either or both surface and sub-surface). Each Hyd parameter has been developed in the model with the same pattern as can be seen by clicking their respective links in the model as shown in Figures 6.6 and 6.7. However, only one parameter, that is precipitation, is selected in order to explain this standard pattern as follows.

When the link 'Preci' in Figure 6.6 is pressed, the action will pop open the form depicted in Figure 6.8. On this form there are four links and their functions are explained as follows. The link 'What is Preci?' when hit, will open a form shown in Figure 6.9. The concept and implications of precipitation are stated in this form particularly in the context of risk assessment of landfill leachate. The same form also contains brief descriptions on the other buttons including Significance Assessment, Uncertainty Assessment and Measuring Preci that sit in Figure 6.8. Once this form (Figure 6.9) has been referred, it can be closed and this action will take the user back to the Form (Figure 6.8).

The button 'Significance Assessment' on the form (Figure 6.8) is to give access to the form shown in Figure 6.10. This form briefly explains what the term 'Significance Assessment' implies in the model overall as well as specifically describes implications of the significance of precipitation parameter with examples. All such descriptions are legible in Figure 6.10, which is a copy directly from the RAM model. The link 'Significance Assessment in general' would take the user to another area of the RAM model, where the Significance Assessment is narrated in much detail as a separate entity of the RAM model. This separate entity is further discussed later in Section 6.7 of this chapter. The 'Back' button is to close the Significance Assessment form and the take the user back to Figure 6.8.

The button 'Uncertainty Assessment' on the form (Figure 6.8) is to give access to the form shown in Figure 6.11. This form briefly explains what the term 'Uncertainty Assessment' implies in the model overall as well as specifically describes uncertainties of precipitation parameter with examples. All such descriptions are legible in Figure 6.11, which is a copy directly from the RAM model. The link 'Uncertainty Assessment in general' would take the user to another area of the RAM model, where uncertainties are narrated in more detail as a separate entity of the RAM model. This separate entity is further discussed later in Section 6.8 of this chapter. The 'Back' button is to close the Uncertainty Assessment form and take the user back to Figure 6.8.

The link 'Measuring Preci' in Figure 6.8 is to access a form shown in Figure 6.12. As the title of Figure 6.12 states, this part of the model is to assist the user estimate precipitation per annum incident on to a given landfill being assessed. The 'General Description' button on the form leads to an area where general guideline for the user is laid down and the 'Specific Description' opens a pane where the user can put down site-specific information regarding precipitation. For instance:

- A risk assessor can discuss what method(s) or source(s) of information have been used to measure or establish precipitation quantity;
- How old the information is, for example which year the precipitation value was estimated;
- Knowledge gaps, if any;
- What are the site-specific uncertainties relating to the precipitation;
- What is the significance of the precipitation in the risk assessment undertaken; etc.

In the RAM computer model to measure a parameter (like groundwater level, leachate quantity, interception, groundwater ingress) methods of measuring have been classified into six categories. These are as follows (Butt et. al., 2006b):

1. Organisation / Authentic body;
2. Field experimental method(s);

3. Laboratory experimental method(s);
4. Empirical method(s);
5. Typical values (for instance, typical leachate constituents of municipal waste landfill in the UK); and
6. Judgement (from relevant experts, such as a meteorologist providing precipitation information for a given landfill region on the basis of the judgement from the national precipitation map, when site-specific data are not available).

The same approach is applied to the precipitation parameter as shown in Figure 6.12. There are six links one for each category of methods listed above. The user can access each category to use any methods of their choice and place precipitation values in the respective categories' forms. As an example of these categories' forms, Figure 6.13 shows the form for the Organisation / Authentic body category of methods. The other five categories' forms are also similar though not shown in this document due to brevity. Figure 6.13 is self-explanatory. There are three columns where values of precipitation can be placed from varoius information sources / legitimate bodies such as a relevant Hydrology Centre or Meteorology Centre. These three columns are maximum, mean / most likely (ML) and minimum precipitation values. The values shown in the figure are just made up examples to support and enrich the explanation of the model functions. Once values are put into the table shown in the figure, the user can switch back to the Figure 6.12 by closing the Figure 6.13 form using the Back button on it. Then select another category of methods to feed precipitation data into the model in the corresponding maximum, mean / ML and minimum fields. Thus, this way precipitation values can be fed into the model for the three columns via various methods in the six categories. Another important feature of the model is that it can accommodate values from the same method applied at different times and / or at different places. For instance, a precipitation gauge placed at a point measuring precipitation at different times in a year can give maximum, mean and minimum values. Similarly, different precipitation gauges placed at different points in the catchment area measuring precipitation at one time can also yield maximum, mean and minimum values. Thus there are temporal and spatial variations for the same method applied. The RAM model is so designed that the categories' forms can take different maximums, means and minimums not only from different methods of different categories but also from the same method applied at different times in different places. And then process the data to bring up these five values (listed below) when the button Work (HAL) button is hit on the form Figure 6.12. These values are also shown in the figure.

1. Highest Maximum Precipitation;
2. Lowest Maximum Precipitation;
3. Mean / Most Likely Precipitation;
4. Lowest Minimum Precipitation; and
5. Highest Minimum Precipitation

All the values from various methods and / or the same method are stored in the table in the model shown in Figure 6.14 for the precipitation parameter. The values in the table do not represent a real scenario but are fictitious numbers, which are chosen arbitrarily as examples. Hitting the 'Workout (HAL)' button runs a 'union query' feature of the RAM model developed with Visual Basic Applications (VBA) embedded in the Microsoft Access (Anakhal, 2000). Running of this query brings out the above five values of precipitation. This concept in the model has been referred to as Penta M or 5 M's and is applicable to a number of other parameters such as interception, runoff, evapo-transpiration. The initial 'HAL' stand for Highest, Average and Lowest as also stated in Figure 6.14.

In Figure 6.12, when the button 'Get the value' is pressed, the 'considered' site area comes from another BS module of the model called Site Management. However, there is a flexibility for the user to put the value there manually, in which case, the value will also be automatically fed into the Site Management module of the BS being inter-connected. The word 'considered' implies that part of the landfill which is being assessed as there could be scenarios where whole of the area of a given landfill need not to be considered in the risk assessment process. For instance, a landfill, which has been partly infilled, completed and closed and the rest is not yet. In such a case, one may be interested to assess only the closed area of the landfill, thus named 'considered' site area. Another example is a landfill, which has been infilled with wastes, and an extension has been proposed. In this case a risk assessor may be assessing only the extension area of the landfill which can also be referred to as 'considered' site area.

From this point onwards in the model (Figure 6.12) only the highest maximum and lowest minimum precipitation values are considered as explained in the figure as well. This covers the whole range of conservativeness from minimum possible to maximum possible. Whereas all the means or most likely values of precipitation are averaged out by the model. All this is executed automatically by the model when the button 'Workout' in Figure 6.12 is clicked. At the same stage in the model, these three precipitation values are also multiplied by the considered site area and the three corresponding results appear in the rows shown in the figure, which are Maximum Precipitation, Mean / Most Likely Precipitation and Minimum Precipitation. The five precipitation values before being multiplied by the area were in head, i.e. metre per year. Whereas after being multiplied by the considered site area the resulting three precipitation values are in volume, i.e. cubic meter per annum.

Figure 6.6: Hydrology Form regarding Waters related to Atmosphere

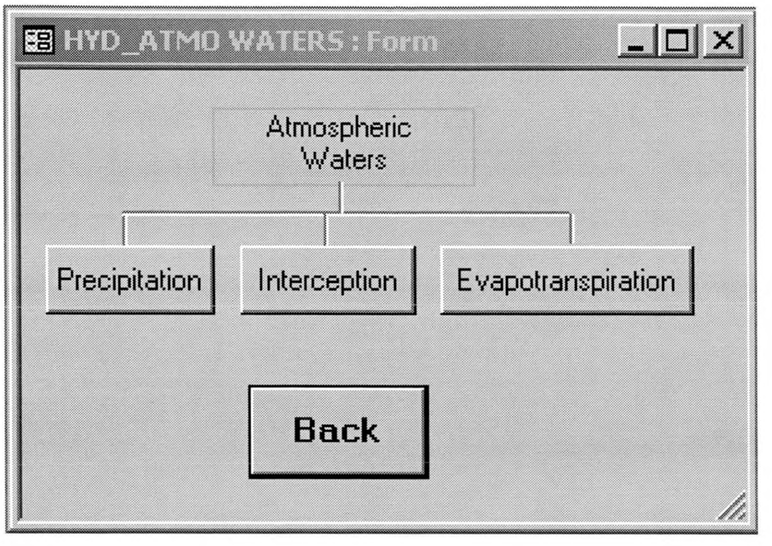


Figure 6.7: Hydrology Form regarding Waters related to Lithosphere

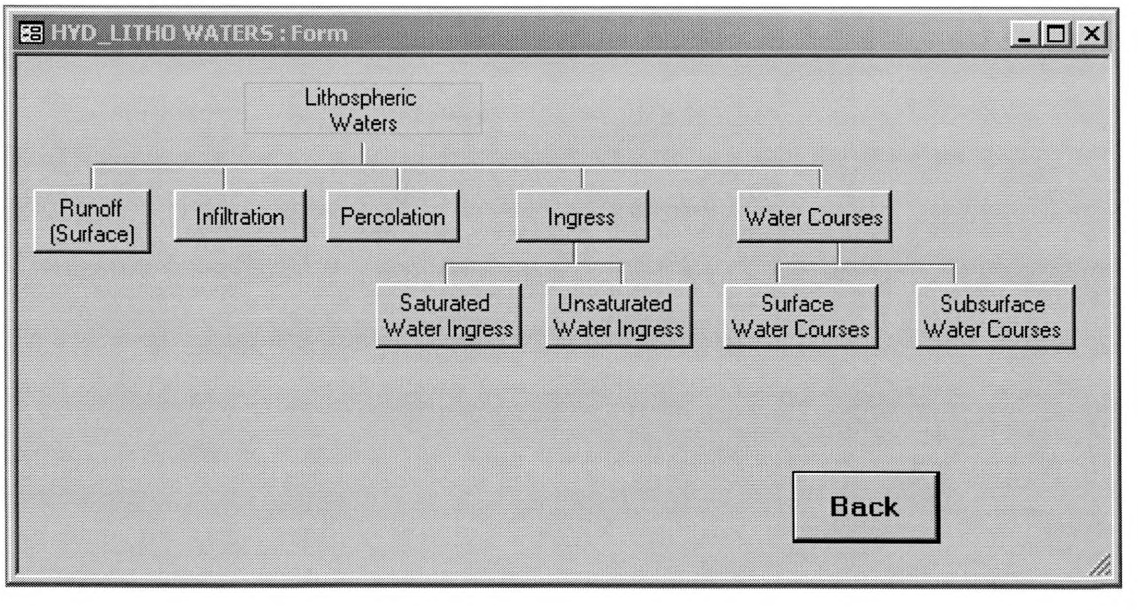


Figure 6.8: Precipitation (Preci) Form in the Hydrology Section of the Model

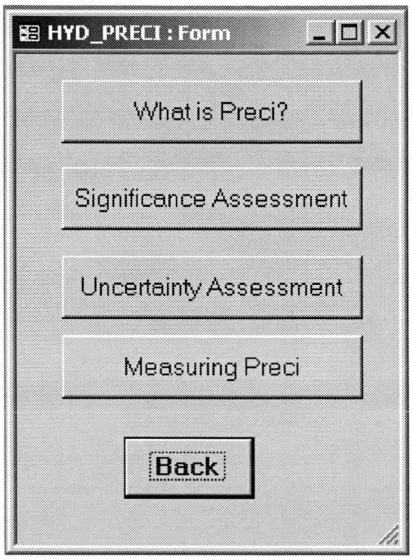


Figure 6.9: 'What is Preci?' Form of the Precipitation Parameter

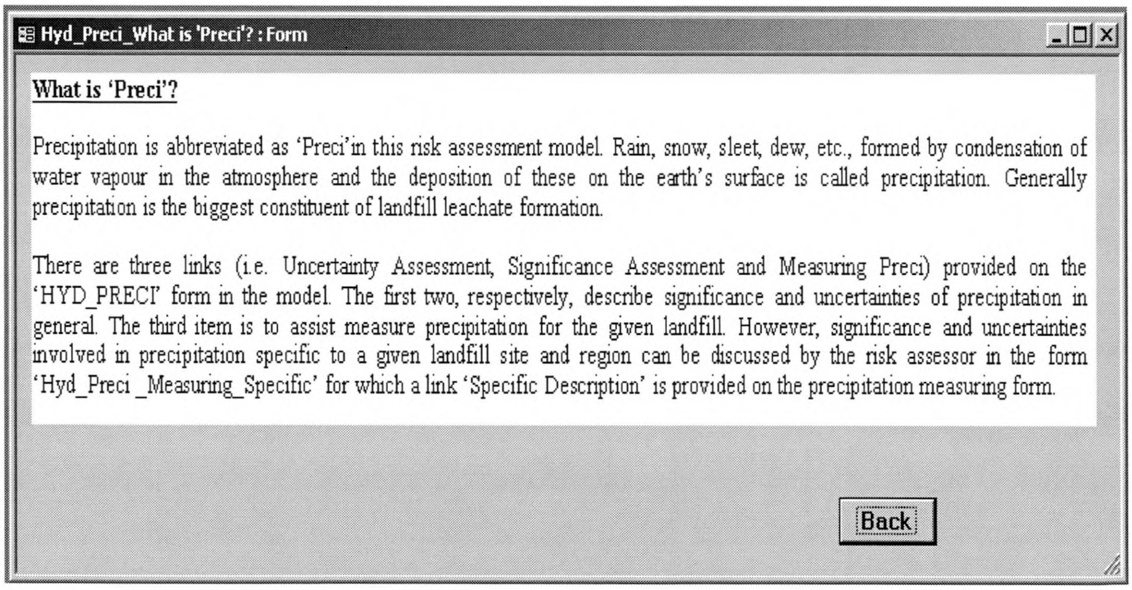
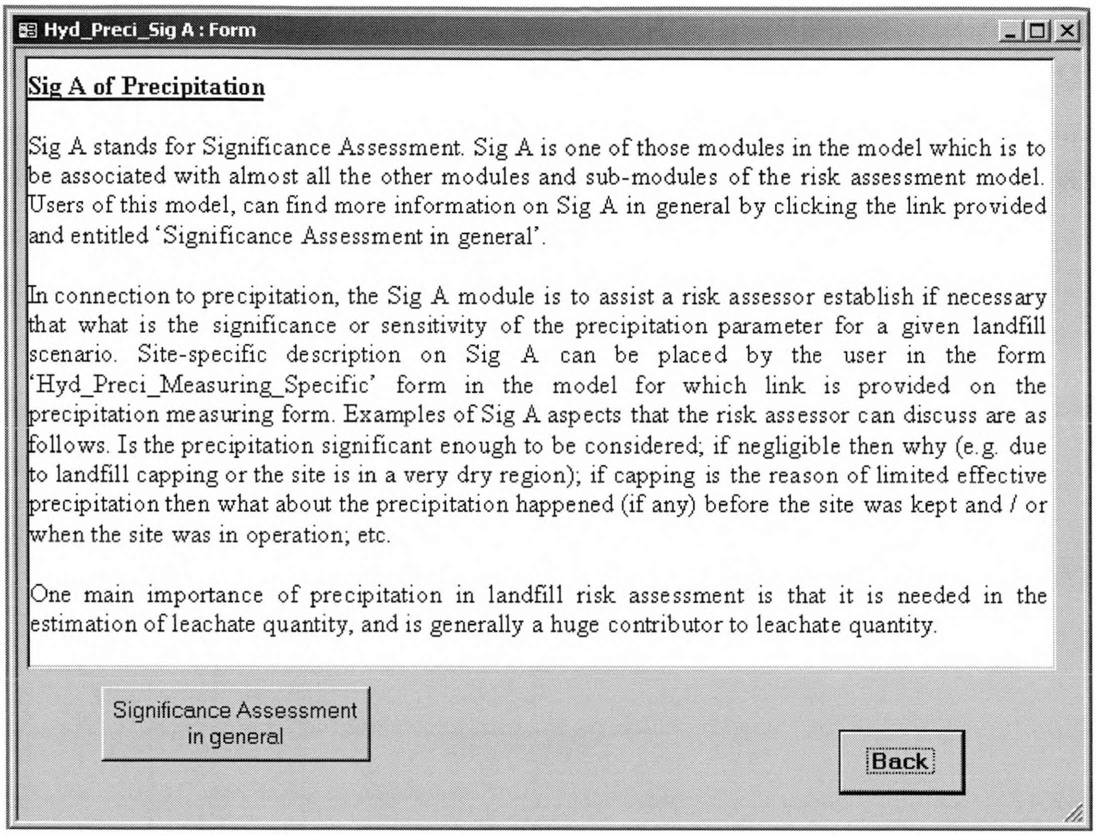


Figure 6.10: Significance Assessment (Sig A) Form of the Precipitation Parameter



Hyd_Preci_Sig A : Form

Sig A of Precipitation

Sig A stands for Significance Assessment. Sig A is one of those modules in the model which is to be associated with almost all the other modules and sub-modules of the risk assessment model. Users of this model, can find more information on Sig A in general by clicking the link provided and entitled 'Significance Assessment in general'.

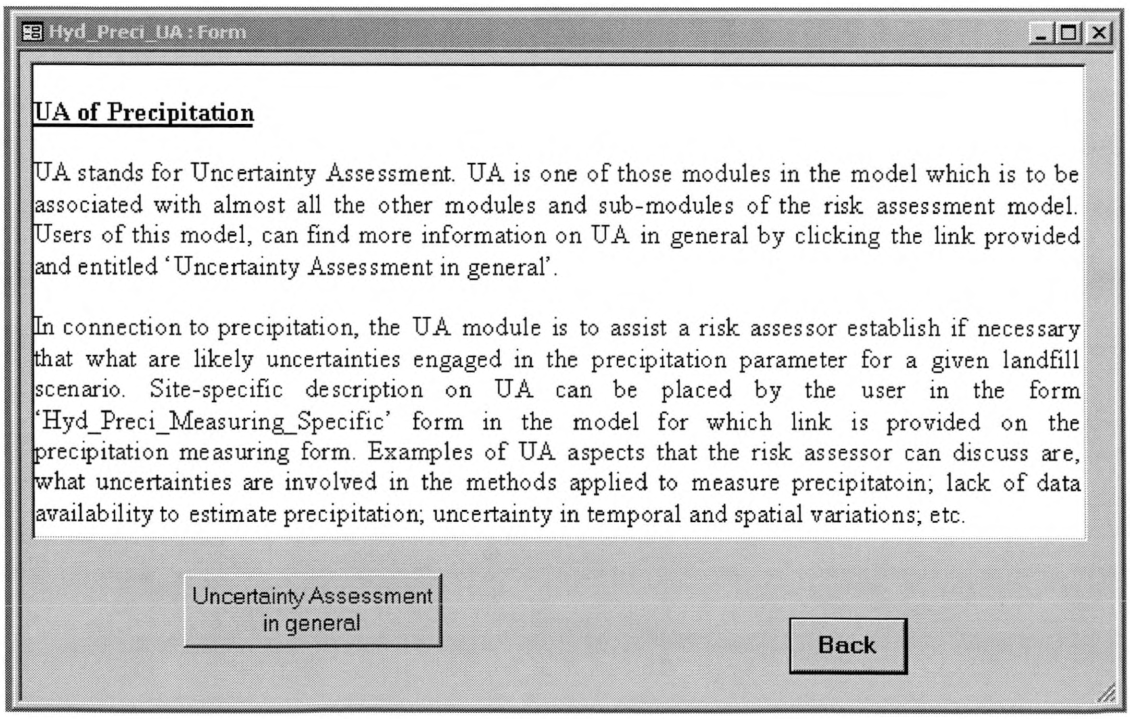
In connection to precipitation, the Sig A module is to assist a risk assessor establish if necessary that what is the significance or sensitivity of the precipitation parameter for a given landfill scenario. Site-specific description on Sig A can be placed by the user in the form 'Hyd_Preci_Measuring_Specific' form in the model for which link is provided on the precipitation measuring form. Examples of Sig A aspects that the risk assessor can discuss are as follows. Is the precipitation significant enough to be considered; if negligible then why (e.g. due to landfill capping or the site is in a very dry region); if capping is the reason of limited effective precipitation then what about the precipitation happened (if any) before the site was kept and / or when the site was in operation; etc.

One main importance of precipitation in landfill risk assessment is that it is needed in the estimation of leachate quantity, and is generally a huge contributor to leachate quantity.

Significance Assessment in general

Back

Figure 6.11: Uncertainty Assessment (UA) Form of the Precipitation Parameter



Hyd_Preci_UA : Form

UA of Precipitation

UA stands for Uncertainty Assessment. UA is one of those modules in the model which is to be associated with almost all the other modules and sub-modules of the risk assessment model. Users of this model, can find more information on UA in general by clicking the link provided and entitled 'Uncertainty Assessment in general'.

In connection to precipitation, the UA module is to assist a risk assessor establish if necessary that what are likely uncertainties engaged in the precipitation parameter for a given landfill scenario. Site-specific description on UA can be placed by the user in the form 'Hyd_Preci_Measuring_Specific' form in the model for which link is provided on the precipitation measuring form. Examples of UA aspects that the risk assessor can discuss are, what uncertainties are involved in the methods applied to measure precipitatoin; lack of data availability to estimate precipitation; uncertainty in temporal and spatial variations; etc.

Uncertainty Assessment in general

Back

Figure 6.12: Precipitation Measuring Form in the Model

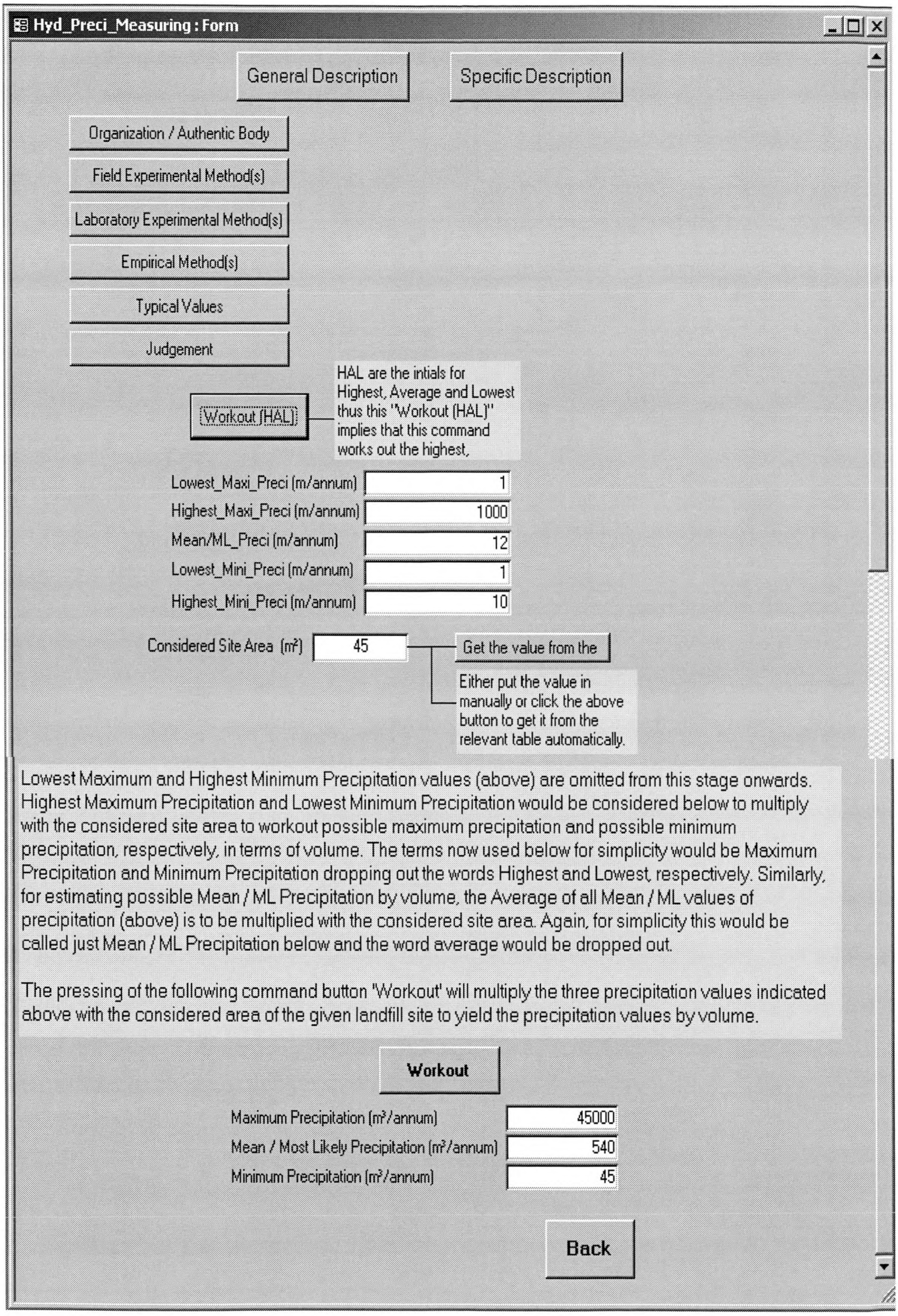


Figure 6.13: Methods' Category Form for Organisation / Authentic body

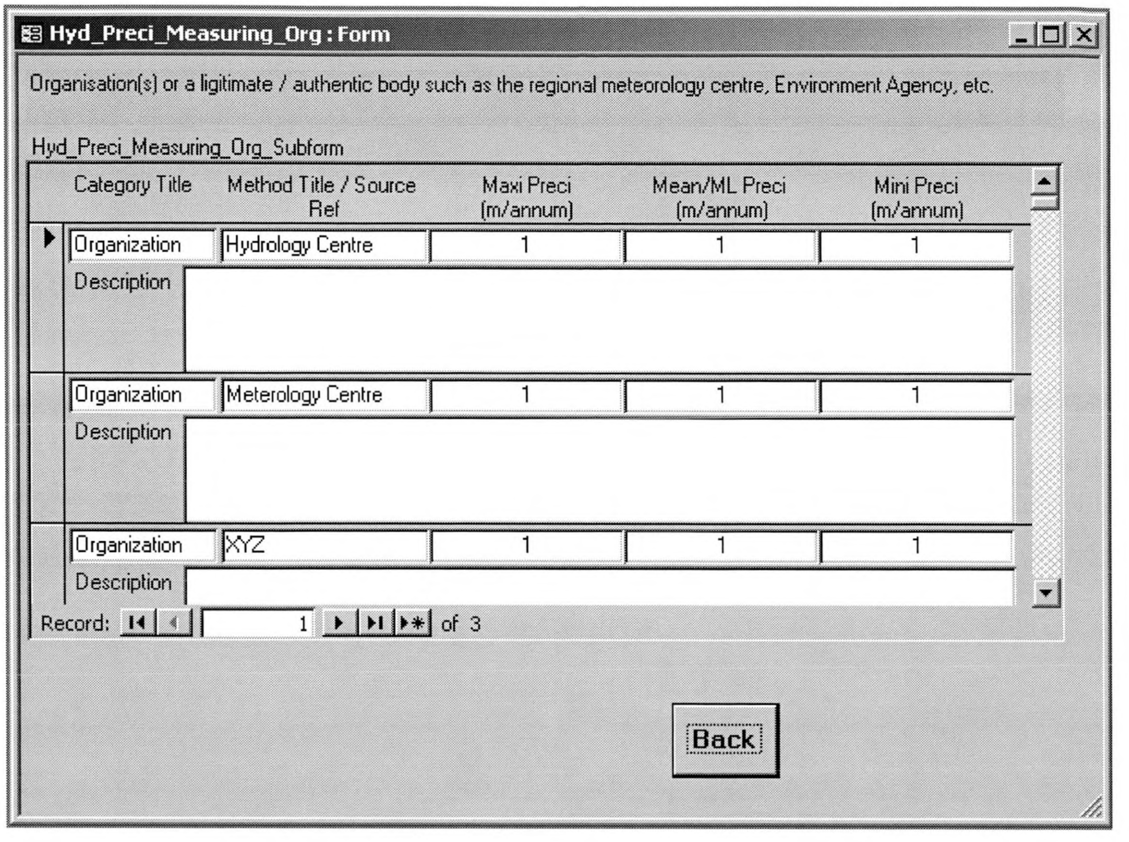
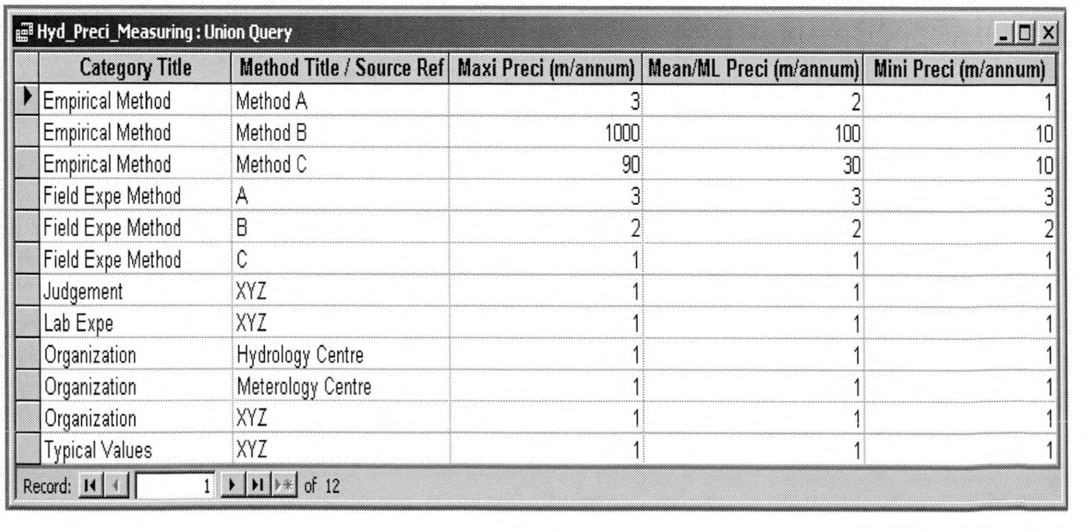


Figure 6.14: 'Union Query Feature' Table in the RAM Model for Precipitation to establish Highest and Lowest Maximum Precipitation Values, Highest and Lowest Minimum Precipitation Values, and Average of Mean / Most Likely Precipitation Values.



Hyd_Preci_Measuring : Union Query

Category Title	Method Title / Source Ref	Maxi Preci (m/annum)	Mean/ML Preci (m/annum)	Mini Preci (m/annum)
Empirical Method	Method A	3	2	1
Empirical Method	Method B	1000	100	10
Empirical Method	Method C	90	30	10
Field Expe Method	A	3	3	3
Field Expe Method	B	2	2	2
Field Expe Method	C	1	1	1
Judgement	XYZ	1	1	1
Lab Expe	XYZ	1	1	1
Organization	Hydrology Centre	1	1	1
Organization	Meterology Centre	1	1	1
Organization	XYZ	1	1	1
Typical Values	XYZ	1	1	1

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6.3 Hazard Identification and Categorisation (H Iden)

After dealing with the BS section of the RAM model above, the risk assessor can switch to the H Iden section. The main menu of the H Iden is shown in Figure 6.15. A 'click' on the buttons H Iden_Quantity, H Iden_Quality, Process and / or Layout, and Harms in the main menu will take a risk assessor to the respective forms of these modules. The basic format of all these four forms is the same, as shown in Figure 6.16, which in this case is specifically for H Iden_Quality and is included as an example (Butt et. al., 2006b).

When the button 'What is H Iden?' in Figure 6.15 is clicked, a form will open up (which is not shown). All the four modules, the H Iden itself, and the terms hazard and risk are defined and explained on this form from the perspective of landfill risk assessment for users' guidance. A click on the button 'Back' in Figure 6.15 will take the risk assessor out of H Iden programme altogether and back to the main page of the RAM computer model (Figure 6.2).

With reference to the first paragraph above, the basic format of the four forms (See Figure 6.16) is very similar. Therefore one of the four i.e. H Iden_Quality module is selected to describe the basic functionality comparatively in more detail as below, rather than describing all four modules each in detail and encountering repetition. In the main menu (Figure 6.15), when the button H Iden_Quality is chosen, its corresponding form will appear as shown in Figure 6.16. In this form, a click on the first button 'What is H Iden_Quality?' will take the user to a form entitled 'What is H Iden?' where H Iden_Quality has been defined and explained. This form is the same and linked with each of the four modules as mentioned in the previous paragraph. This form can be closed once it has served the purpose of explaining H Iden_Quality terminology to the user. The buttons 'Significance Assessment' and 'Uncertainty Assessment' in Figure 6.16, when selected, will reveal two different forms, one explaining the significance, and the other uncertainties that could be involved in H Iden_Quality, in general. A risk assessor can discuss the significance and uncertainties involved in the H Iden_Quality for a specific case in a separate form. This form is not shown because of brevity. The risk assessor can open this separate form by clicking on the button 'Specific Description'. This button is shown in Figure 6.17, which is discussed below.

When the button 'Identifying H Iden_Quality' (Figure 6.16) is clicked a form will appear as shown Figure 6.17. In this form the button 'General Description' provides access to a form (not shown) where a few aspects of H Iden_Quality module are described as a guideline for the user. For instance, how this module relates to other parts of the RAM computer model in terms of mutual information transport; how this module can be effectively used; groupings of quality hazards into toxicants, non-toxicants, carcinogens and non-carcinogens. The button 'Specific Description' (Figure 6.17) is to provide a form where a user can narrate, for instance, why and what methods are applied to identify hazards; any uncertainties involved in the methods. Thus the format of the computational tool is so designed that it addresses issues in general in the form of guideline as well as there is allocated space available for the user to describe these issues specific to a given landfill scenario. The button 'Back' when clicked will close this form (Figure 6.17) and risk assessor will be back to the previous form (Figure 6.16).

With reference to the table shown in Figure 6.17, the first column / field named 'Quality Hazard Name' will contain a list of all the site-specific pollutants and properties of a given landfill leachate. These hazards once specified would automatically appear in the other relevant modules and sub-modules of the RAM computer model, for example, Exposure Quantification, hazard Concentration Assessment (See Sections 6.4 and 6.5 of this chapter below). This demonstrates the mutual interconnections, or mutual information transport between the H Iden and other parts of the RAM model. In the second column (Figure 6.17) a user can choose to differentiate a given quality hazard as a pollutant, or as a property of the leachate. Similarly in the third column it can be specified that the quality hazard is toxic, or non-toxic, or both. In the event that the hazard is toxic or both, the user can indicate in the fourth column that it is carcinogenic, non-carcinogenic or even both. However, if a given quality hazard is non-toxic for a scenario (e.g. a river as a receptor which can not have toxic affects), then the fourth column is to be left blank. A drop down menu is available in the second, third and fourth columns to choose from the above options in order to avoid having to enter the information on each occasion. The second to last column enables the user to specify the potential harm that may arise from a given quality hazard. The last field is used to describe anything else that a user finds relevant to elaborate the given hazard. For example, a given pollutant may exist in the List 1 or List 2 substances of the Groundwater Directive. On the right hand side there is provided a 'Vertical Scroll Bar' with which a user can scroll up and down the list of hazards on the form.

It must be noted that if in a risk assessment iteration for a given landfill being assessed the environmental receptor is, e.g. non-living such as a river, the risk assessor must choose the 'non-toxic' option for each quality hazard in the third column for two reasons. Firstly, to indicate that the considered non-living receptor is independent of toxicity effects therefore non-toxic is the most relevant option in the third column for the quality hazards. Secondly, the programming of the computer model is designed to have a selection in the third column to perform its calculations in the later stages of the risk assessment process in the Hazard Indices (See Section 6.9). The same principle or computer model limitation applies when a quality hazard is toxic or both (toxic and non-toxic) then the third column should contain either carcinogenic or non-carcinogenic or both (carcinogenic and non-carcinogenic), in order to enable the computer programme to operate its calculations to workout corresponding hazard indices. Figure 6.17 depicts this in the relevant fields / columns as well as shows a note regarding this for the RAM model user as a guideline.

Like H Iden_Quality module, the other three modules also have sections and buttons in the similar manner for Significance Assessment, Uncertainty Assessment, General Description, and Specific Description. Therefore, the rest of the discussion focuses on differences in functionality between the three modules. As mentioned in Section 6.2 above, the methods of measurement of parameters have been categorised into the six groups. The same approach is applied to the module on leachate quantity estimation (See Figure 6.18). This figure is a form for leachate quantity measurement in the H Iden_Quantity module.

The leachate quantity of a given landfill can be estimated in a number of ways. One example is an empirical method of a mass balance or water budget approach. This will involve several factors including, precipitation, interception, evapo-transpiration, run-off, groundwater ingress, and liquid wastes, if any. This approach is particularly useful when a landfill does not exist in a physical sense but in design and planning stage. If a landfill is at, for instance, completed and closed stage then leachate quantity can also be measured on the basis of average leachate head per annum multiplied by the site's area. This leachate head may be derived by employing a software such as LandSim. A landfill assessor may not have to literally carry out an exercise of leachate quantification every time or in every scenario, as such information may already be available from other legitimate sources, such as the Environment Agency, landfill operator, or environmental monitoring data of the site. Similarly, for the category of Field Experimental Method(s), if leachate head or level per annum of a given landfill is measured on-site then simply multiplying the figure by the area of landfill, the leachate quantity can be determined. Keeping in view the maximum, most likely and minimum leachate levels (for instance, round the year), the corresponding maximum, most likely and minimum leachate estimates can be made. This way temporal variations can be addressed. In order to account for spatial variations leachate head need to be measured at different points on the landfill site area. In the Judgement category of methods, hydrogeologists' and meteorologists' expertise may be relied upon to estimate leachate quantity using hydro-geological maps and precipitation maps. There are no methods available for leachate quantity estimation in the category of Laboratory Experimental Method(s) and Typical Values. Therefore each of these two has a label 'None' attached to them as shown in Figure 6.18.

With reference to Section 6.2, the computer tool can store results from more than one method used to measure / estimate leachate quantity of a given landfill being assessed. Moreover, the model is also capable to store values from the same method employed at different times. As shown in Figure 6.18, when the button 'Workout' is clicked, the model will run a programme embedded in the model to workout maximum, mean / most likely and minimum leachate quantities. These three quantities will be derived from the set of all the values fed into the model from various leachate quantification methods applied at various times in a given time period, for instance, around a year. This programme is an 'union query' based as explained earlier in Section 6.2 for Precipitation parameter. However, these worked out maximum, most likely and minimum leachate quantities can be used in the later stages of the RAM computer model to assess worst case (i.e. maximum), most likely and least bad (i.e. minimum) risk scenarios, respectively. This information can be useful as a reflection on concentrations of the quality hazards in the exposure medium and receptor boundaries for a given landfill scenario being assessed.

A click on the button 'H Iden_Process and / or Layout' in Figure 6.15 will open a form (shown in Figure 6.19), which has eight buttons. These eight buttons are connected with eight forms on one to one basis. All these eight forms (not shown here) have the same format. There are general guidelines provided in each of the eight forms to assist the risk assessor on what kind of information should be considered and brought up from the Baseline Study in the context of risk to describe in this 'Process and / or Layout' module. For instance, in the geology section of the Baseline Study of the RAM computer model, a landfill assessor would have gathered the information on porosity of bedrock under the given landfill. In the 'Geology Hazards' form (of the Process and / or Layout module of the H Iden), the landfill assessor can refer to this information of the BS geology module from the perspective of risk like this. Since the porosity of the bedrock under the given landfill is high therefore the risk of environmental pollution is high as well. Similarly, on the basis of the information from the hydrogeology module of the Baseline Study the landfill assessor can state in the 'Hydrogeology Hazards' form (of the Process and / or Layout module of the H Iden) that the presence of an unsaturated zone between a given landfill base and the highest groundwater point indicates a comparatively low risk of pollution. On the contrary, the absence of such a zone may lead to an enhanced risk of environmental pollution. Due to this relationship between Process and / or Layout module and BS section, links are made available on the eight forms corresponding to the eight modules of the BS (See the RAM Model for further details).

A click on the button Harms in Figure 6.15 will lead the user to a form (not shown here), which provides guidelines about potential harms in general. With the help of these general guidelines, the landfill assessor on this form can describe and discuss site-specific potential harms posed by the lechate hazards established earlier in the other three modules of the H Iden by the assessor (Butt et. al., 2006b).

Figure 6.15: The Main Front Page / Menu of the 'H Iden' Form in the RAM Model

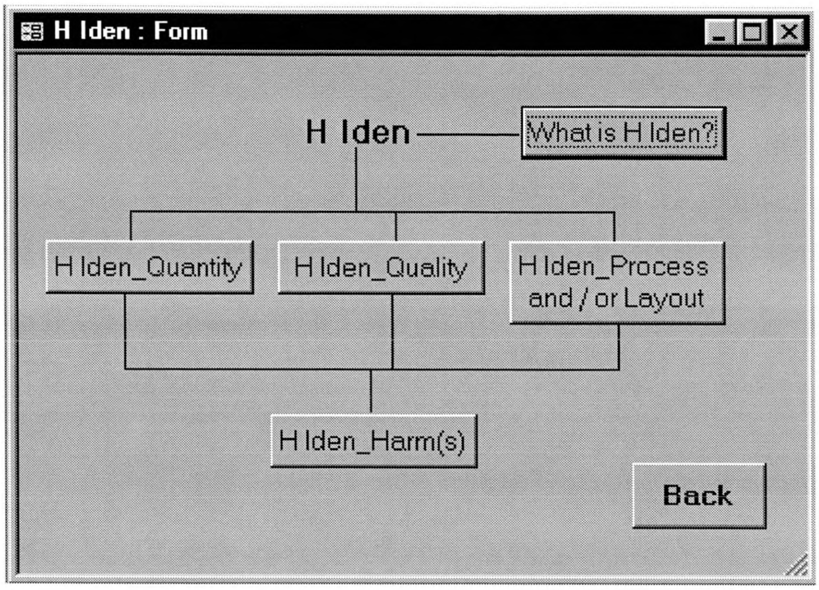


Figure 6.16: The Main Front Page / Menu of the 'H Iden_Quality' Form in the Model

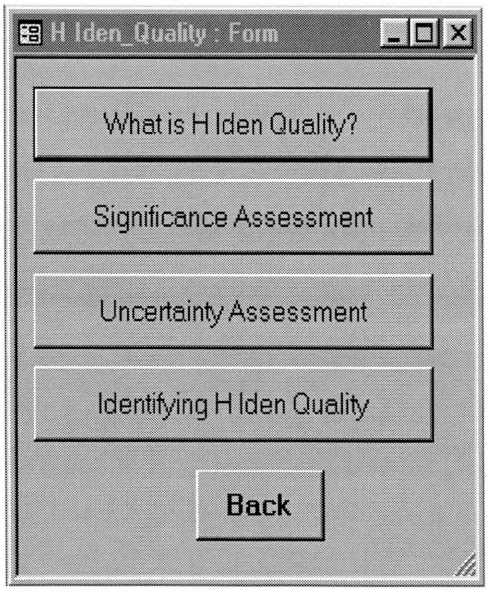
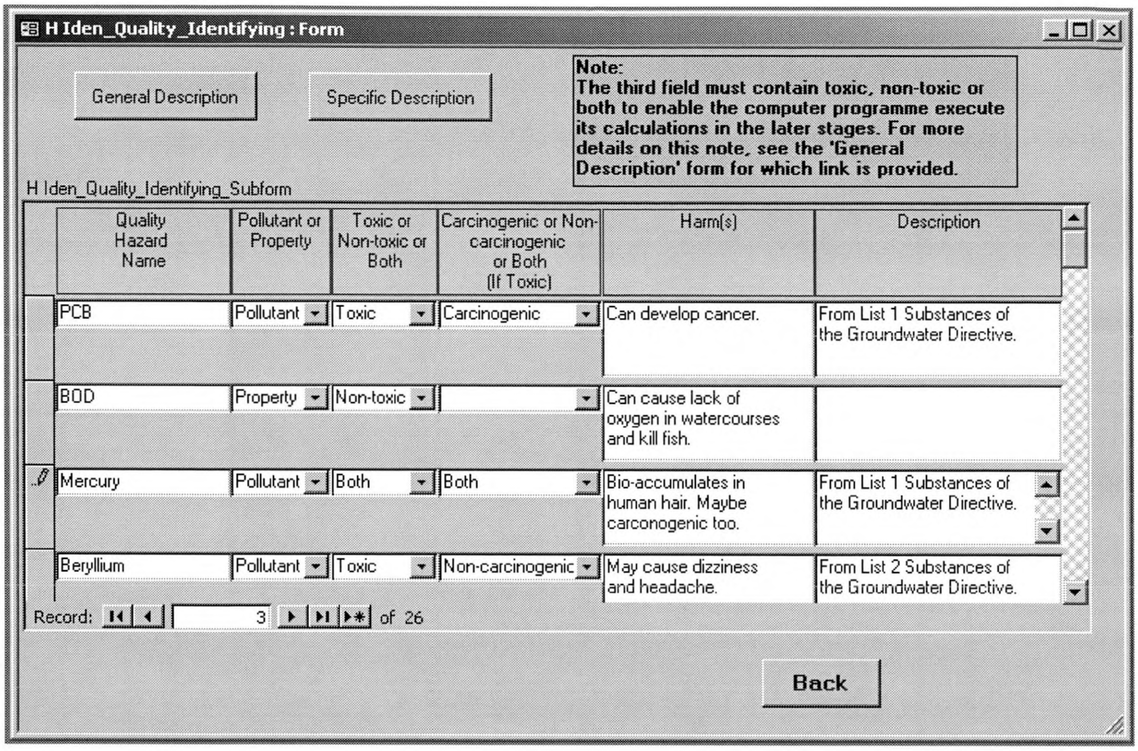


Figure 6.17: The 'Leachate Quality Identification' Form in the Model



H Iden_Quality_Identifying : Form

General Description

Specific Description

Note:
The third field must contain toxic, non-toxic or both to enable the computer programme execute its calculations in the later stages. For more details on this note, see the 'General Description' form for which link is provided.

H Iden_Quality_Identifying_Subform

Quality Hazard Name	Pollutant or Property	Toxic or Non-toxic or Both	Carcinogenic or Non-carcinogenic or Both (If Toxic)	Harm(s)	Description
PCB	Pollutant	Toxic	Carcinogenic	Can develop cancer.	From List 1 Substances of the Groundwater Directive.
BOD	Property	Non-toxic		Can cause lack of oxygen in watercourses and kill fish.	
Mercury	Pollutant	Both	Both	Bio-accumulates in human hair. Maybe carconogenic too.	From List 1 Substances of the Groundwater Directive.
Beryllium	Pollutant	Toxic	Non-carcinogenic	May cause dizziness and headache.	From List 2 Substances of the Groundwater Directive.

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Figure 6.18: The 'Leachate Quantity Measuring' Form in the Model

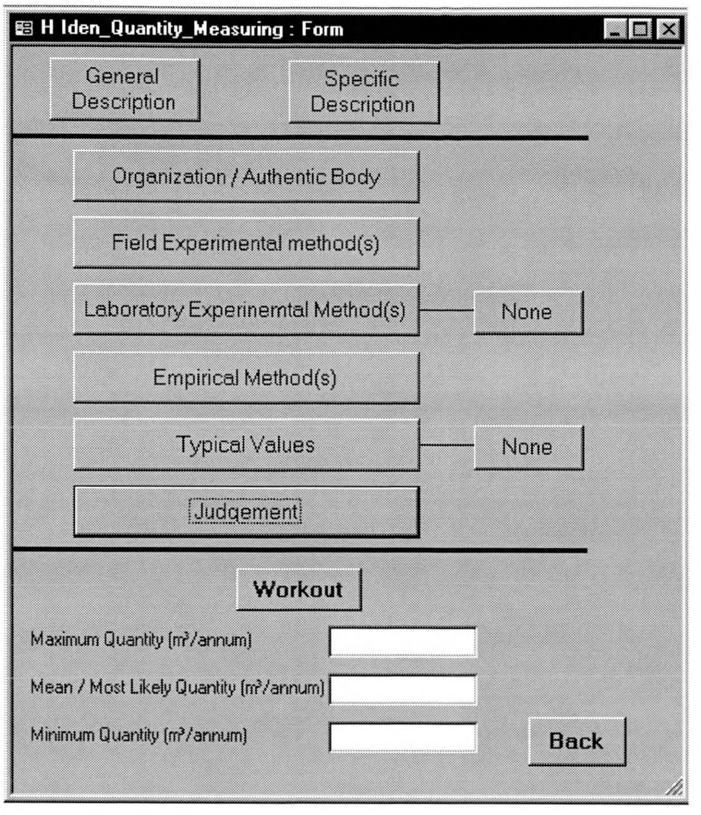
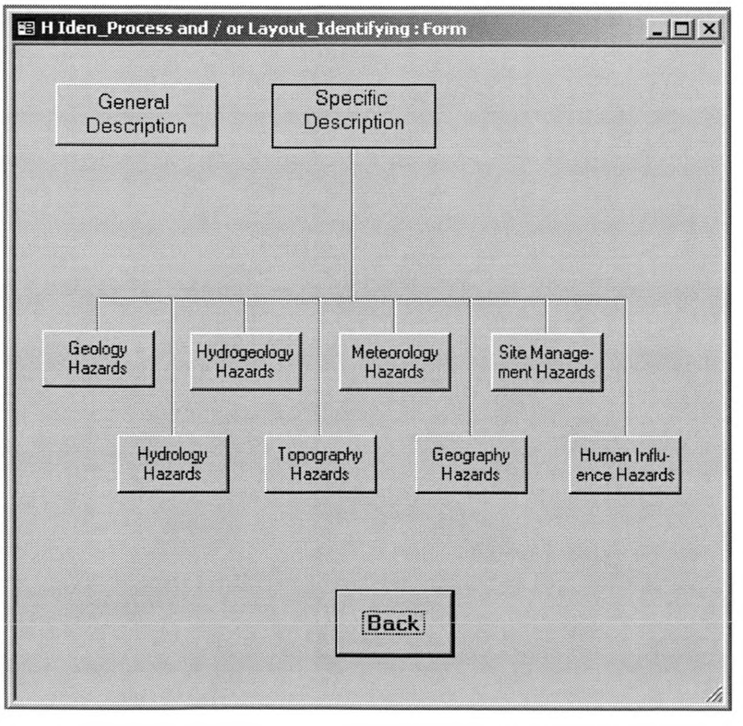


Figure 6:19: The 'Process and / or Layout Hazards Identification' Form in the Model



6.4 Exposure Assessment (Ex A)

The main menu of the Ex A in the RAM model is shown in Figure 6.20. The options Sorc Iden, P Iden, T Iden and Ex Quan in the menu, will take a risk assessor to the separate forms of Source Identification (and Categorisation), Pathway Identification (Categorisation), Receptor / Target Identification (and Categorisation) and Exposure Quantification, respectively. Each form would appear in the format shown in Figure 6.21. However, Figure 6.21 is specifically for Ex Quan.

The first three modules (i.e. Sorc Iden, P Iden, and T Iden) are not described any further in this chapter as enough details have already been given in Chapter 5. These three modules have been developed in the RAM model along the same lines as narrated in the previous chapter. However, the form of Exposure Quantification (Figure 6.21), which is objective in nature, is taken further in the following paragraphs. The model also contains a form, which defines and briefly explains the four modules (i.e. Sorc Iden, P Iden, T Iden and Ex Quan) from the perspective of landfill risk assessment. This form can be accessed via 'What is Ex A?' link (where 'Ex A' is an abbreviation for Exposure Assessment), as shown in Figure 6.20. The 'Back' link in Figure 6.20 will take a risk assessor out of Exposure Assessment programme altogether and back to the main page of the RAM computer model.

The function 'Ex Quan' (Figure 6.20) will open a form, as shown in Figure 6.21, with four options. In this form, 'What is Ex Quan?' option will open the form where Ex Quan has been defined and explained. The functions 'Significance Assessment' and 'Uncertainty Assessment' in Figure 6.21 lead to the forms where the significance and uncertainties that could be engaged in Exposure Quantification, respectively, are explained. A risk assessor can discuss the significance and uncertainties related to the Exposure Quantification for a specific case, in a separate form (not shown here for the reason indicted in the summary of this chapter in the beginning). This form can be accessed via 'Specific Description' link (shown in Figure 6.22). This Figure 6.22, which is accessed via the 'Measuring Exposure' link in Figure 6.21, is discussed below.

The form shown in Figure 6.22 is in relation to measuring individual exposures across various exposure routes and then aggregating them. This form is equipped with a number of features. The first feature 'Units' links a form (not shown) where a risk assessor can describe and explain units they are adopting for exposure measurement. The second, 'General Description', connects a form (not shown) where different aspects of Exposure Quantification have been described in general. These include factors constituting exposure (such as exposure frequency, exposure duration) and their mutual relationships; possible exposure routes leading to a receptor; and various methods of measurement of exposure where some exposure equations have also been described in this form. This form also indicates that calculations, if any, for Exposure Quantification have to be performed outside the computer model and then the results from the external process will be fed back into the model. The reason is that calculations and equations / approaches vary hugely from scenario to scenario in many ways, where the range of scenarios is very wide and yet all possible scenarios are not known. Thus, accommodation of such equations and calculations for such a huge variety of scenarios in the computer model was going to complicate the model. Although, at this stage of the research study some databases are provided in the model and as a flexibility feature a risk assessor is given the choice to decide on which equations / approaches to use for quantifying or measuring exposure. However, in the form accessible via the 'Specific Description' link mentioned earlier, a risk assessor can also discuss what exposure equations / approaches, how and why they have been used for a specific case.

In the table shown in Figure 6.22, the first column / field named 'Quality Hazard' contains a list of all the site-specific pollutants (like Cd, Hg, Co) and / or properties (such as pH, hardness, Chemical Oxygen Demand) of leachate that are hazardous to the environment. Thus, the term 'Quality Hazard' refers to both pollutants and properties of leachate. In fact, these hazards would have already been identified in the H Iden of the RAM model as mentioned earlier (Section 6.3, above) and thus automatically appear in the first field of the form shown in Figure 6.22. With reference to Chapter 5, four exposure routes are considered in the model. For each exposure route, there are maximum, mean and minimum values of exposure which a risk assessor can feed into the model, as may be required for a given risk assessment. The last three columns /

fields in Figure 6.22 are simply the summation of corresponding fields indicated above. This summation process can be activated by the link 'Ex A_Ex Quan (t=ing+der+inh+oth) where t, ing, der, inh and oth are abbreviations for total, ingestion, dermal contact, inhalation and 'others if any', respectively. However, the default values for all exposure routes are zero unless over ridden by the risk assessor. So far as the function at the bottom of Figure 6.22 'CA_PC_Ex MCf_Measuring' is concerned, it relates to the Concentration Assessment (CA) section of the RAM model. In the CA a risk assessor would have already worked out final concentrations of pollutants in the Exposure Medium (abbreviated Ex MCf) for a given landfill scenario being risk assessed (Butt and Oduyemi, 2003). These Ex MCf values, in fact, would be needed in exposure equations to calculate exposure. Thus, this link is provided to allow the risk assessor to access the information in the CA. Further details on this are set out in the following section of this chapter.

Figure 6.20: The Main Front Page / Menu of the 'Exposure Assessment' Form

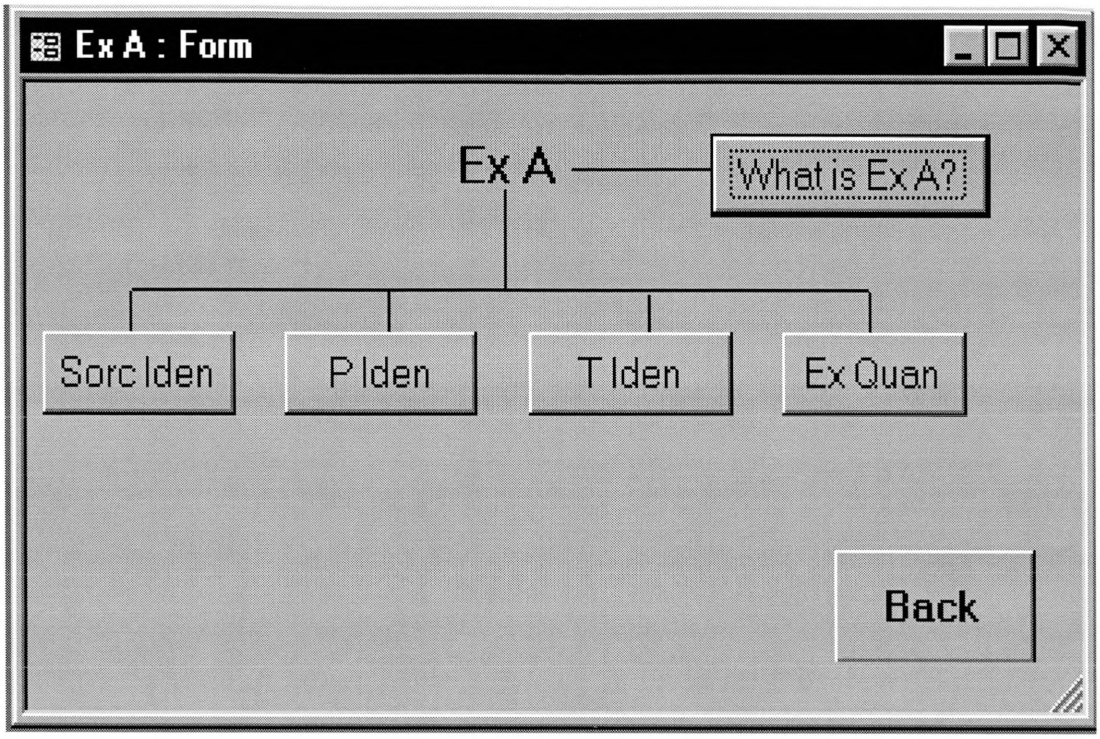


Figure 6.21: The Main Front Page / Menu of the 'Exposure Quantification' Form

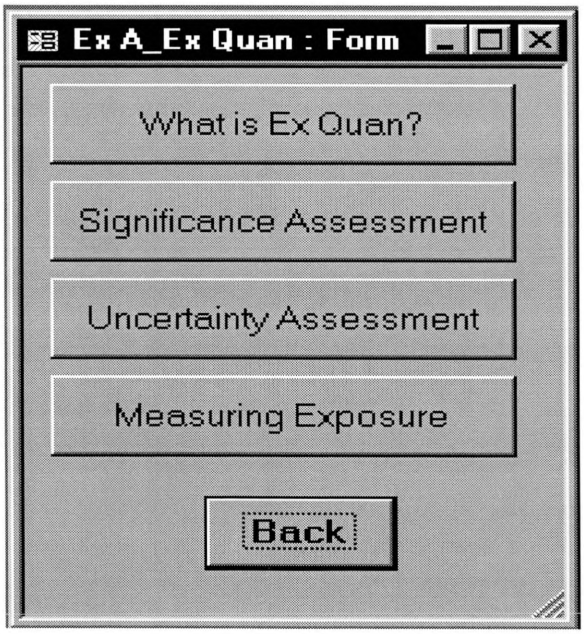
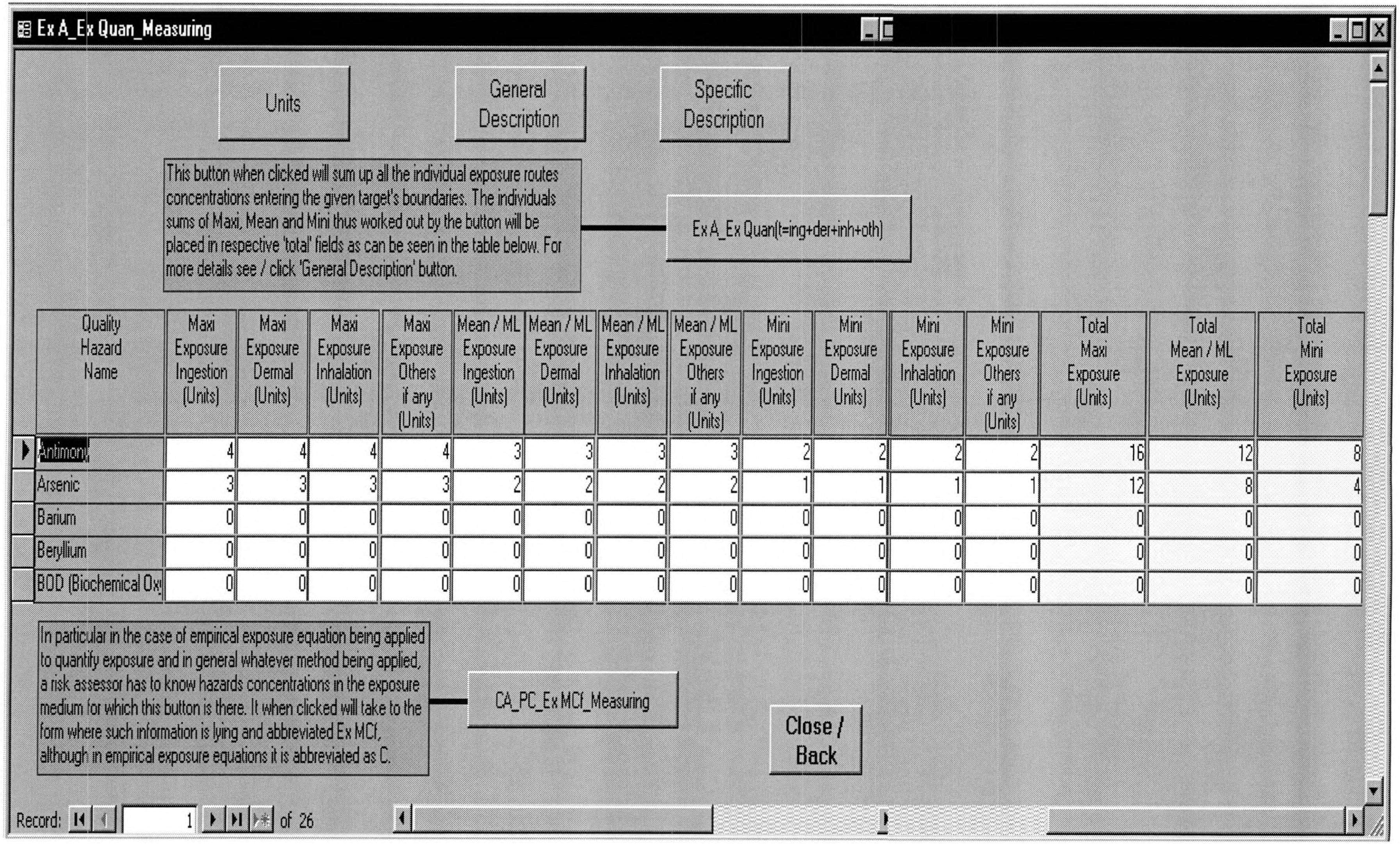


Figure 6.22: The 'Exposure Measuring' Form in the Model



Ex A_Ex Quan_Measuring

Units

General Description

Specific Description

This button when clicked will sum up all the individual exposure routes concentrations entering the given target's boundaries. The individuals sums of Maxi, Mean and Mini thus worked out by the button will be placed in respective 'total' fields as can be seen in the table below. For more details see / click 'General Description' button.

Ex A_Ex Quan(t=ing+der+inh+oth)

Quality Hazard Name	Maxi Exposure Ingestion (Units)	Maxi Exposure Dermal (Units)	Maxi Exposure Inhalation (Units)	Maxi Exposure Others if any (Units)	Mean / ML Exposure Ingestion (Units)	Mean / ML Exposure Dermal (Units)	Mean / ML Exposure Inhalation (Units)	Mean / ML Exposure Others if any (Units)	Mini Exposure Ingestion (Units)	Mini Exposure Dermal Units)	Mini Exposure Inhalation (Units)	Mini Exposure Others if any (Units)	Total Maxi Exposure (Units)	Total Mean / ML Exposure (Units)	Total Mini Exposure (Units)
Antimony	4	4	4	4	3	3	3	3	2	2	2	2	16	12	8
Arsenic	3	3	3	3	2	2	2	2	1	1	1	1	12	8	4
Barium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Beryllium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BOD (Biochemical Ox	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

In particular in the case of empirical exposure equation being applied to quantify exposure and in general whatever method being applied, a risk assessor has to know hazards concentrations in the exposure medium for which this button is there. It when clicked will take to the form where such information is lying and abbreviated Ex MCf, although in empirical exposure equations it is abbreviated as C.

CA_PC_Ex MCf_Measuring

Close / Back

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6.5 Concentration Assessment (CA)

The main front page of the Concentration Assessment is shown in Figure 6.23. The buttons Sorc C, PC, TC and Cri C, when clicked, will take a risk assessor to the respective forms Source Concentration, Pathway Concentration, Receptor / Target Concentration and Critical Concentration modules and each would appear as shown in Figure 6.24. However, Figure 6.24 is specifically for Final Target Concentration (TCf). With reference to Chapter 5, PC and TC are further divided into their sub-modules. The buttons for accessing these sub-modules are provided in the model as shown in Figure 6.23. A click by a risk assessor on any of the buttons of the sub-modules will 'pop' up forms with exactly the same format as shown in Figure 6.24, which is further discussed below to explain other functional features of the model. However, in Figure 6.23 a click on the button 'What is CA?' will open up a form (not shown here). All the four modules (Sorc C, PC, TC and Cri C) along with their sub-modules, and CA are defined and explained on this form from the perspective of landfill risk assessment. A click on the button 'Back' in Figure 6.23 will take a risk assessor out of Concentration Assessment programme altogether and back to the main page of the RAM computer model (Butt and Oduyemi, 2003).

Figure 6.24 illustrates the form of TCf (Final Target Concentration). A click on the first button 'What is TCf?' will show the form where TCf has been defined and explained. This form is the same as already mentioned above (i.e. 'What is CA?'). In Figure 6.24 the buttons 'Significance Assessment' and 'Uncertainty Assessment', when clicked, will 'pop' up two different forms, one explaining the significance, and the other uncertainties, that could be involved in concentration analysis, in general. A risk assessor can discuss the significance and uncertainties involved in the concentration analysis for a specific case in a separate form (not shown here). The risk assessor can open this form by clicking on the button 'Specific Description' (shown in Figure 6.25) (Butt and Oduyemi, 2003).

When the button 'Measuring TCf' (Figure 6.24) is clicked, the form shown in Figure 6.25 will 'pop up'. In this form a click on the button 'Units' opens another form (not shown here) where a risk assessor can describe and discuss units they are adopting for concentration measurements. The button 'General Description' opens a form (not shown here) where different aspects of Final Target Concentration have been discussed in general. These include examples of scenarios when Initial Target Concentrations (i.e. TCi) need to be considered and when they may be omitted; mass balance equations to work out the TCf when Initial and Intake Target Concentrations have been taken into account, depending on a number of factors such as nature and size of the given target. In a scenario where initial or background concentration of a hazard is zero or negligibly zero then the model will automatically consider the background concentration of the hazard to be zero by default. Similarly, the 'General Description' forms of sub-modules TCi, Sorc C, Ex MCi, etc. (not shown here) also discuss a range of other aspects. These include spatial and temporal variations and how to take account of them in measuring concentrations of hazards; various methods of measurement; and calculations to be carried out outside the model and why. In Figure 6.25, the buttons just above the table namely 'CA_TC_TCi_Measuring' and 'CA_TC_Intk C_Measuring' are provided to access the measuring forms of Initial and Intake Concentrations, respectively, for a given target. This facility is there in order to assist in the combination of the two concentrations to work out the final concentration using the mass balance equation indicated in Section 5.5 of Chapter 5. This is also explained in a text box next to these two buttons (Figure 6.25); in order to make the risk assessor aware of where various features are located (Butt and Oduyemi, 2003).

With reference to the table shown in Figure 6.25, the first column / field named 'Quality Hazard' contains a list of all the site-specific pollutants and properties of leachate that are hazardous to the environment. In fact, these would have already been identified in the H Iden section of the RAM computer model. Once these hazards for a given landfill are identified they automatically appear in this field in the form shown in Figure 6.25. These hazards will also spontaneously appear in other relevant forms of modules and sub-modules such as TCi, Intk C, Sorc C, Ex MCf, Ex MCi (not shown), where a risk assessor has to work out the concentration levels and feed values in these forms. These forms, although not shown in this document, have a similar format to that shown in Figure 6.25 for TCf and can be seen in the RAM model attached in the form a CD.

A brief functional example of the HA part of the RAM model (Butt and Oduyemi, 2003; Butt et. al., in press – b)

The application of the RAM model is described as a validation exercise in Chapter 7. However, an example is described below to further elaborate on the RAM model. The example does not represent a real but fictitious scenario in order to depict the functionality of the model particularly but briefly focusing on the first four sub-parts / sections of the RAM model described above. Consider a two year closed landfill pollutant source with six boreholes sunk into its body for leachate sampling. The landfill is existing such that its bottom lies 5 m above water-table. Thus, effective unsaturated zone would be 5 m deep. Below 5 m, all the way down exists saturated zone till it meets to sit on an aquifer, which is 15 m further below, such that the effective saturated zone depth is 15 m and the aquifer is in total 20 m below the landfill base. This aquifer leads downstream to a live stock of a fish farm, which is situated at a horizontal distance of 1000 m downstream from the landfill, where there is a groundwater abstraction well sunk into the aquifer. Fish farm water is to be recharged / supplemented from that well, which can be seen as an exposure medium. So, in total, the three intermediate media or links constitutes the pathway from landfill source to the fish farm water. These are, the unsaturated zone (5 m), saturated zone (15 m), and aquifer length 1000 m. All the above information would have been collated by the risk assessor in the 'Baseline Study' and 'Exposure Assessment' sections of the RAM computer model.

For the H Iden stage of the hazard and risk assessment process, samples of leachate collected from various bore-holes of the landfill site over the last two years of post-closure of the site indicate the presence of following (property and pollutant) hazards, namely BOD, pH, ammonial-nitrogen, zinc and copper. The landfill manager can advise or inform the leachate quantity. This leachate quantity can be estimated using mass balance approach if the landfill manager does not have up to date information on leachate generated per annum. One process and / layout hazard worth considering is that no capping, no interception loss, no likely runoff and yet no leachate is pumped off site but only circulated back into the landfill body. Therefore, leachate quantity is almost the same as the precipitation. All the information mentioned in this paragraph, can be allocated among these respective sub-sections of the H Iden. That is 'H Iden Quality', 'H Iden Quantity' and 'Process and / or Layout Hazard'. That accomplishes the H Iden phase of the RAM.

When the risk assessor clicks the button CA of the RAM computer model, this action will open up the main front page of the CA as shown in Figure 6.23. The click of the button 'Sorc C' will pop open the module 'Source Concentration' which would appear in the same format as in Figure 6.24, which though is for 'Final Target Concentration'. In this 'Source Concentration' module, concentrations of the above named pollutants are considered over two years in the given six boreholes. The highest concentration shown for each pollutant in any borehole, any time during the given period can be seen as that pollutant's possible maximum concentration in the landfill. Similarly, the lowest concentration of the same pollutant in any borehole, any time during the period can be taken as possible minimum concentration of the pollutant in the landfill. To work out the most likely or mean concentration of the pollutant, average out its concentrations in the given boreholes and over time. This way, spatial and temporal variations may be taken into account to a reasonable extent. The maximum, most likely / mean and minimum concentrations thus worked out for the above five pollutants from leachate samples (with whatever approach / method applied) can be placed in the table provided in the 'Sorc C'. In this example these values are worked out to be as shown in Table 6.1. However, in the computer model, this table would appear with all its accessories just like that shown in Figure 6.25 which is for 'Final Target Concentration'. Nevertheless, for simplicity and due to brevity in this chapter, this table and other following tables are as shown in Table 6.1 i.e. without the accessories. With the help of geometric information on the landfill an effective centre of landfill body could be figured out which can be used as 'point source' to measure distance between landfill and items like exposure medium, receptor / target, etc. This work can be laid in the 'Sorc Iden' module of Ex A section where some guidelines are also provided for a risk assessor to carry out this work. Once this 'effective centre' of the landfill body is decided, this information can be used in the P_Iden module of the Ex A section of the RAM model to determine lengths of various media and / or pathways. This is indicated earlier (in the first paragraph of the example) where the lengths of media or links are established. This is how relevant information can be used in the model from one module into another. However, in the given examples these media lengths are already fictitiously / arbitrarily established in the first paragraph of this example description.

Once 'Source Concentration' work is accomplished above, the risk assessor will go back to the main front page of Concentration Assessment (Figure 6.23) and click the button 'PC' in order to pop open the module 'Pathway Concentration'. The unsaturated zone, saturated zone and aquifer are pre-exposure media or links of the given pathway and thus can be dealt with in the Pre-Exposure Medium Concentration sub-module (abbreviated Pre Ex MC in Figure 6.23). It is up to a risk assessor if they want to break down each individual pollutant's concentration before reaching the exposure medium, across the above named intermediate links of the pathway by using an appropriate approach, e.g. an empirical method, LandSim software, HELP model, etc. This would help to show how the given pollutant concentrations are varying along the pathway's various links. However, pollutant concentrations reaching the exposure medium (which is groundwater abstraction point in the given scenario) is the matter of prime concern. This is dealt with in the sub-module 'Exposure Medium Concentration - Reaching' form which can be popped open by clicking the button 'Ex MCr' in the main front page (Figure 6.23). Like the 'Sour C', this sub-module also allows maximum, most likely / mean and minimum concentrations of the five pollutants reaching the exposure medium which can be worked out using any approach by a risk assessor say LandSim. The values thus worked out are shown in Table 6.2. Like Table 6.1, Table 6.2 is also not shown with its full accessories as mentioned above.

Maximum, mean and minimum initial concentrations of the five pollutants in the given exposure medium can be established from samples taken from the groundwater abstraction point and analysed in a laboratory. These maximum, mean and minimum values can be placed in the table of the corresponding sub-module called Exposure Medium Concentration - Initial (abbreviated Ex MCi) form. This form can be accessed using the button 'Ex MCi' in Figure 6.23, and the form would appear the same as Figure

6.25 which though is for sub-module regarding target concentration. If the existing water quality is such that it is free of pollutants the default zero values in the computer model can be applied. In this example it is assumed that existing pollutant concentrations are zero. These zero values automatically appear in the computer model for the given five pollutants. However, the initial maximum, initial mean and initial minimum concentrations of the given pollutants once established (either default zeros or whatever) can be added to the corresponding Ex MCr values by using a mass balance approach. And the results can be placed in the sub-module 'Final Exposure Medium Concentration' (abbreviated Ex MCf). This form can be accessed via the button 'Ex MCf' in the main front page (Figure 6.23) and it would appear the same as Figure 6.25 which is for the 'Final Target Concentration'. Since the Ex MCi values are assumed to be zero in this example, therefore the same Ex MCr values would be placed in the Ex MCf form as shown in Table 6.3.

Once the 'Exposure Medium Concentration' section is completed, the risk assessor will go back to the main front page of Concentration Assessment (Figure 6.23) to deal with the module Target Concentration. The fish farm water is the receptor / target to which groundwater from the water abstraction well is to be added. The click on the button TCi (Figure 6.23) would lead to the sub-module 'Initial Target Concentration' form which would appear the same as Figure 6.25. In this form, maximum, mean and minimum values of initial target concentrations of the five given pollutants can be put. These values can be figured out, e.g. by analysing samples from the fish farm water. In this example, TCi values for the five pollutants are assumed to be zero as if existing fish farm water is free of these pollutants. Therefore default values of the computer model i.e. zeros are applied. After this, the click on the button 'Intk C' (abbreviating Intake Concentration) on the main front page (Figure 6.23), would provide access to the form where maximum, mean and minimum values of the given five pollutants' concentrations being taken in by the target from the water well can be put. In the example under consideration, these maximum, mean and minimum values are the same as in Exposure Medium - Final since the water from the same medium is to be discharged in to the farm pool. Therefore the same Ex MCf values can be fed into this form, correspondingly.

The sub-module TCf (abbreviating 'Final Target Concentration') can be accessed by the click of the button TCf in the front main page (Figure 6.23). The form where final concentrations of the given five pollutants are to be placed appears as shown in Figure 6.25. In the light of the information on TCi and Intk C sub-modules discussed above, TCf can be worked out by applying a mass balance approach as described in the model earlier. These TCf values will be achieved for maximum, mean and minimum scenarios from the corresponding maximum, mean and minimum values in the TCi and Intk C forms discussed above. In this example, the dilution factor after adding groundwater from the abstraction point has been omitted for simplicity. And also TCi values are assumed to be zero, therefore TCf values for the five pollutants (see Table 6.4) would be the same as Intk C values which are the same as Ex MCf values in this scenario.

From the relevant literature review one can determine the safe levels of concentrations of the given five pollutants for fish. For instance, the classification system is set out in the Surface Waters (River Ecosystem) Classification Regulations, 1994 (SI, 1994b). For the above five pollutants, critical concentrations or criteria prescribed are shown in Table 6.5. These are for the highest quality river water and the same can be considered for the fish farm water. These concentrations would be fed into the form of the Critical Concentration section which would be accessed via the button 'Cri C' on the main front page (Figure 6.23). This form will appear in the same format as shown in Figure 6.25, which is for TCf. However, for simplicity and due to brevity only the table of Cri C form is shown without other accessories and buttons. The values of the given five pollutants from Cri C and TCf forms can be compared with each other correspondingly to determine hazard indices and risk potentials in the subsequent sections or factors of the RAM model. These subsequent sections of the model are elaborated below.

Figure 6.23: The Main Front Page of 'Concentration Assessment' Form in the Model

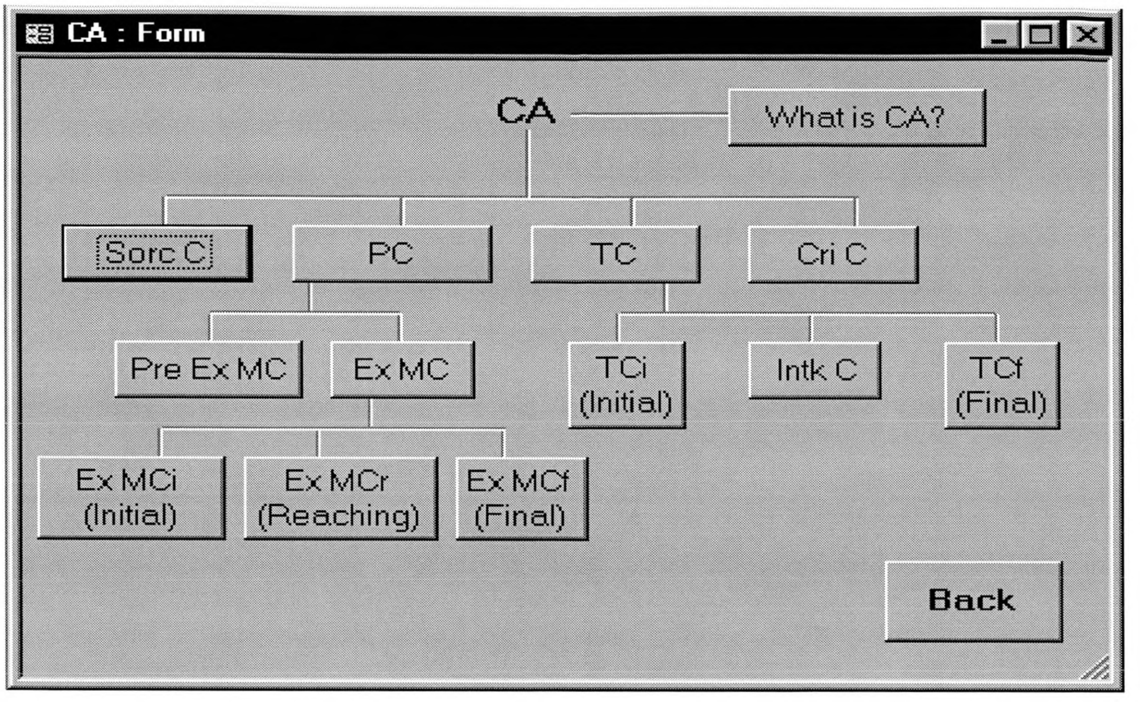


Figure 6.24: The Main Front Page of 'Final Target Concentration' Form

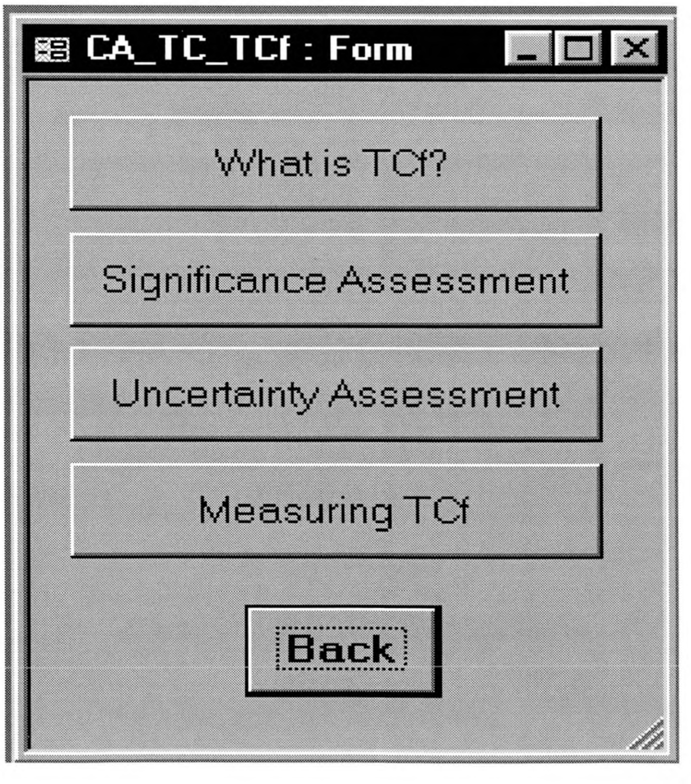


Figure 6.25: 'Final Target Concentration Measuring' Form in the Model

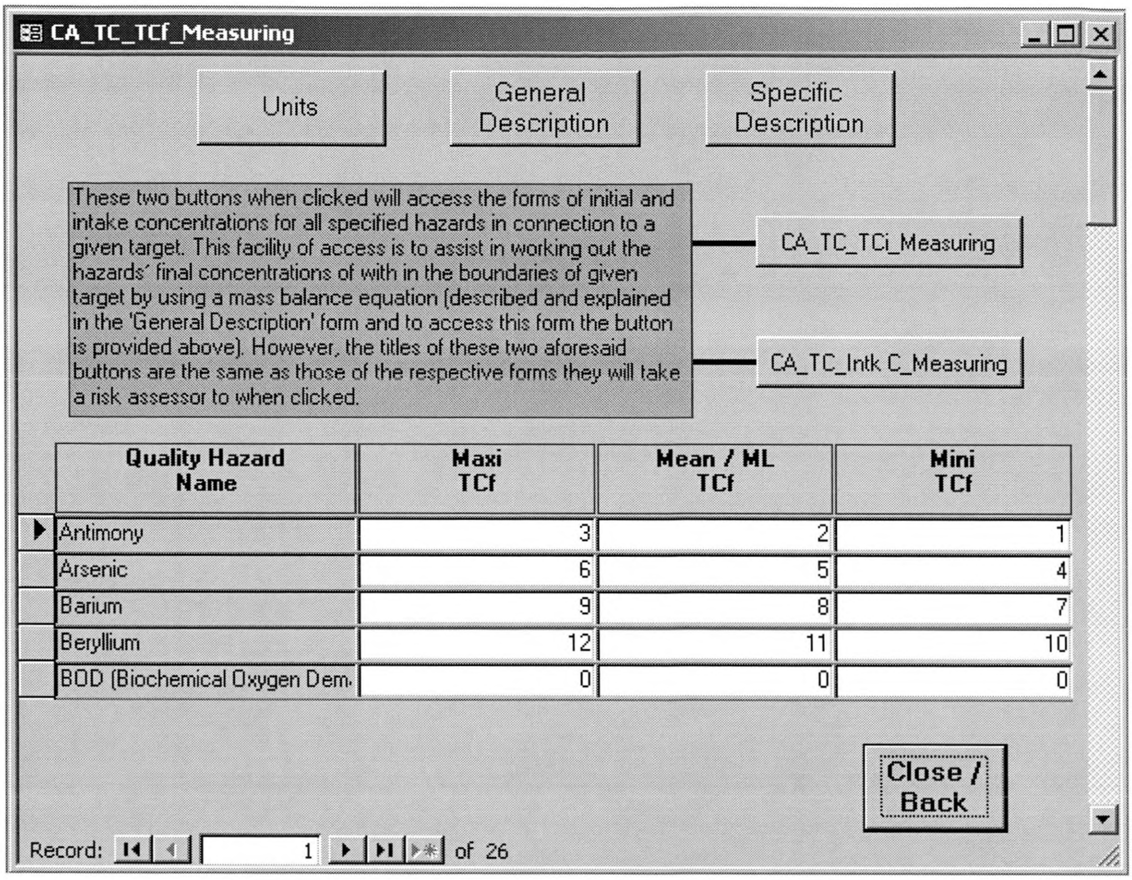


Table 6.1: Concentration of Quality Hazards at the Source (mg / l)

Quality Hazard Name	Maxi Sorc C	Mean / ML Sorc C	Mini Sorc C
BOD	41	39	30
pH	0.9	0.8	0.7
Ammonial - N	30	29.8	25
Zinc	0.6	0.47	0.39
Copper	0.2	0.17	0.15

Table 6.2: Concentrations of Quality Hazards Reaching the Exposure Medium (mg / l)

Quality Hazard Name	Maxi Ex MCr	Mean / ML Ex MCr	Mini Ex MCr
BOD	38	35	28
pH	0.8	0.7	0.6
Ammonial - N	28	24	22
Zinc	0.4	0.35	0.29
Copper	0.15	0.1	0.08

Table 6.3: Final Concentrations of Quality Hazards in the Exposure Medium (mg / l)

Quality Hazard Name	Maxi Ex MCf	Mean / ML Ex MCf	Mini Ex MCf
BOD	38	35	28
pH	0.8	0.7	0.6
Ammonial - N	28	24	22
Zinc	0.4	0.35	0.29
Copper	0.15	0.1	0.08

Table 6.4: Final Concentrations of Quality Hazards in the Receptor / Target (mg / l)

Quality Hazard Name	Maxi TCf	Mean / ML TCf	Mini TCf
BOD	38	35	28
pH	0.8	0.7	0.6
Ammonial - N	28	24	22
Zinc	0.4	0.35	0.29
Copper	0.15	0.1	0.08

Table 6.5: Critical Concentrations of Quality Hazards for the Target (mg / l)

Quality Hazard Name	Maxi TCf
BOD	2.5
pH	0.6 - 0.9
Ammonial - N	0.25
Zinc	0.005
Copper	0.030

6.6 Migration Assessment (Migra A)

A click on the button Migration Assessment in the Main Front page of the RAM model (Figure 6.2), will lead the risk assessor to the form shown in Figure 6.26 which is the main menu of the Migration Assessment section of the model. The link 'What is Migra A?' in Figure 6.26 is to access a form where all the terms or parameters shown in the figure are explained for quick reference of the landfill assessor. This form, however, is not shown here. These terms include:

- Migra A – Migration Assessment
- Migra – Migration
- Attenu – Attenuation
- Ex MCr (Reaching) – Reaching Exposure Medium Concentration
- Verti Migra – Vertical Migration
- Hori Migra (Advection) – Horizontal Migration
- Dispr – Dispersion
- Retar – Retardation
- Phy – Physical reactions
- Che – Chemical reactions
- Bio – Bio-chemical / Biological reactions
- Sorp – Sorption
- CER – Cation Exchange Reaction
- Dil – Dilution
- Abso – Absorption, and
- Adso – Adsorption

The link 'Ex MCr' in Figure 6.26 is to lead the landfill assessor to the form shown in Figure 6.27, which is the main front page of the 'Reaching Exposure Medium Concentration (Ex MCr)' in the Migration Assessment section of the RAM computer model. The format of this form is exactly the same as for the other modules and sub-modules of the RAM model described earlier in this chapter. The button 'What is Ex MCr?' will pop open the same form (not shown) where all Migration Assessment terms, including Ex MCr, have been described as a 'on hand' reference for the user. Once the model user has benefited from this form, it can be closed to get back to Figure 6.27. The links Significance Assessment and Uncertainty Assessment will be performing the same functions as stated earlier for the other modules and sub-modules of the RAM model.

The button 'Measuring Ex MCr' (Figure 6.27) will open a form shown in Figure 6.28. In this form, the links Units, General Description and Specific Description are for the same counter-purposes as explained earlier for the sub-modules such as Ex Quan and TCf. The first field is the list of quality hazards (both pollutants and / or properties). There are three columns for maximum, mean / most likely and minimum concentrations of these quality hazards that reach the exposure medium such as a groundwater course. The last field is to establish the probability of the concentration of each quality hazard reaching the exposure medium. This probability feature maybe further developed in future research (not only for Ex MCr but also e.g. Intk C and concentrations in other pathway media before an exposure medium such as saturated zone, unsaturated zone). However, at this stage in this research project the software such as ConSim and LandSim can assist to establish these probabilities as the LandSim is for probabilistically estimating possible concentrations of various pollutants reaching an exposure medium in the hydro-geosphere (McMahon et. al., 2001). For instance, the LandSim programme can indicate that the probability of a given pollutant's concentration to reach a groundwater abstraction point from the landfill in 30 years is 50%. Expanding further on this, if a laboratory experimental method is applied on samples taken from the groundwater abstraction point after 30 years or a field experimental method is employed 30 years later to measure the pollutant's concentration in the groundwater abstraction point. Then the probability is 100% for whatever concentration is measured, as this is not probabilistically estimated before time rather practically after the given period of time (30 years). In other words, 'the hindsight is always better than the foresight'.

Irrespective of whatever method(s) used, once the maximum, mean / most likely and minimum values of Ex MCr derived for all the identified leachate 'quality hazards', these can be placed in the respective fields of the form specified in Figure 6.28. These values will automatically appear in the Ex MCr form of the Concentration Assessment section of the RAM model, which is an example of backward information transfer in the RAM computer model. In the Migra A section of the RAM model the module 'Ex MCr' is completed where as the other modules 'Migra' and 'Attenu' and their sub-modules are not accomplished in this model at this stage, and being left for further research work. Therefore, unlike Ex MCr link, the buttons of these modules and sub-modules are not hyperlinks in the RAM model's form shown in Figure 6.26. However, if the RAM model is being applied to a given landfill risk assessment, these modules and sub-modules may automatically be covered by the LandSim programme if used, depending on the characteristics of a given landfill scenario being assessed. If laboratory or field experimental methods are applied, examples given in previous paragraph, then these module and sub-modules become irrelevant.

Figure: 6.26 The Main Front Page / Menu of Migration Assessment in the Model

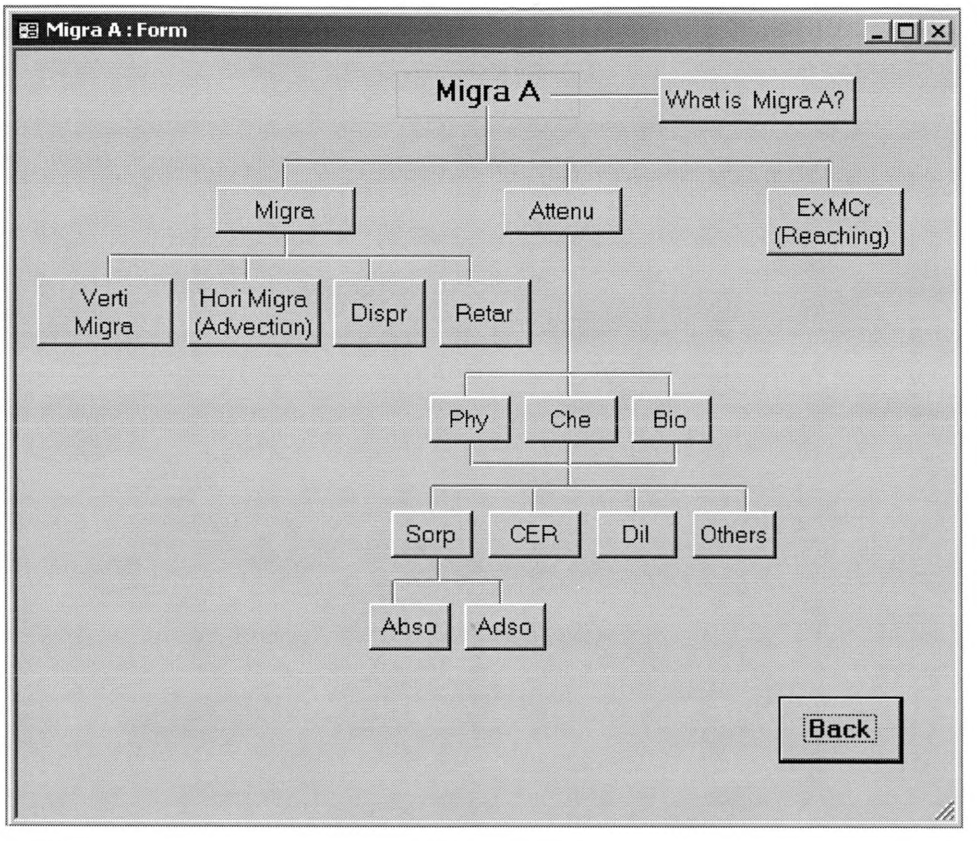


Figure 6.27: The Main Front Page of 'Exposure Medium Concentration (Reaching)' Form in the Migration Assessment Section of the RAM Model

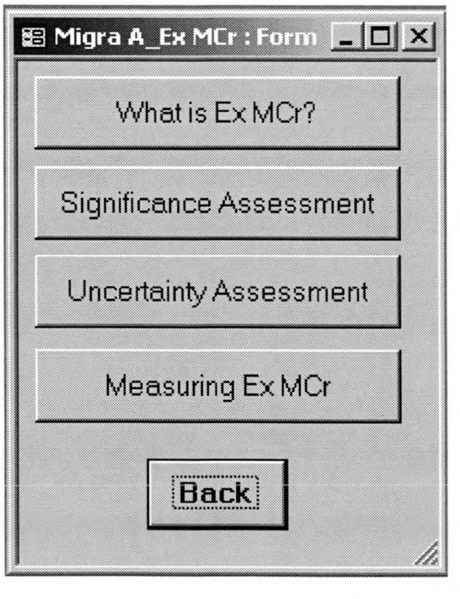
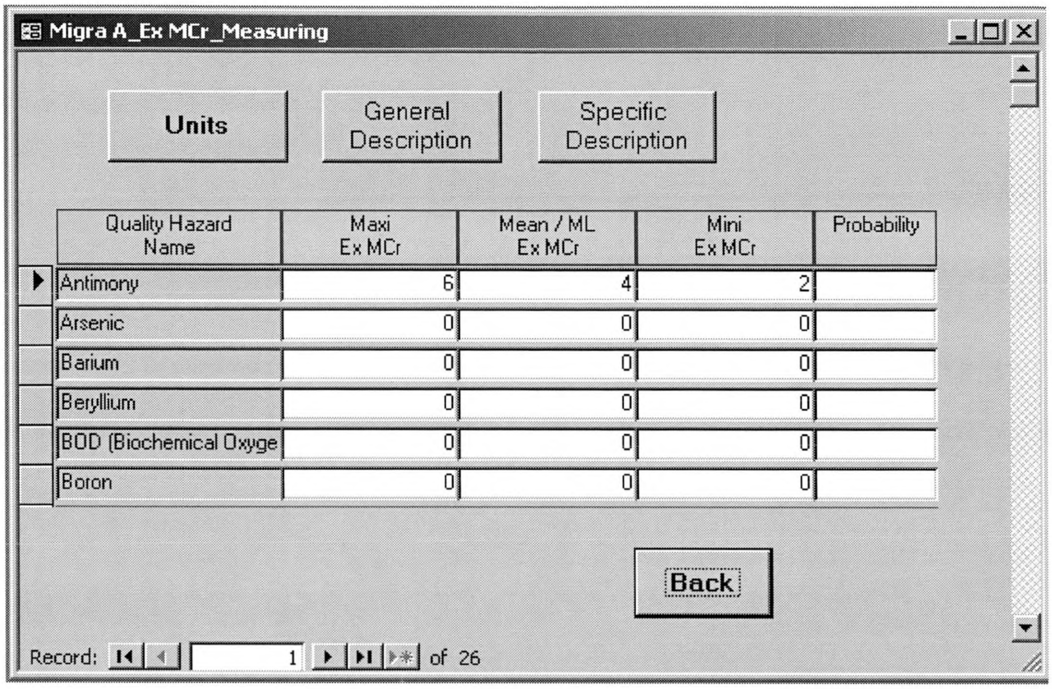


Figure 6.28: Measuring Form of 'Exposure Medium Concentration (Reaching)' in the Migration Assessment Section of the RAM computer Model


Migra A_Ex MCr_Measuring

Units | General Description | Specific Description

Quality Hazard Name	Maxi Ex MCr	Mean / ML Ex MCr	Mini Ex MCr	Probability
Antimony	6	4	2	
Arsenic	0	0	0	
Barium	0	0	0	
Beryllium	0	0	0	
BOD (Biochemical Oxyge	0	0	0	
Boron	0	0	0	

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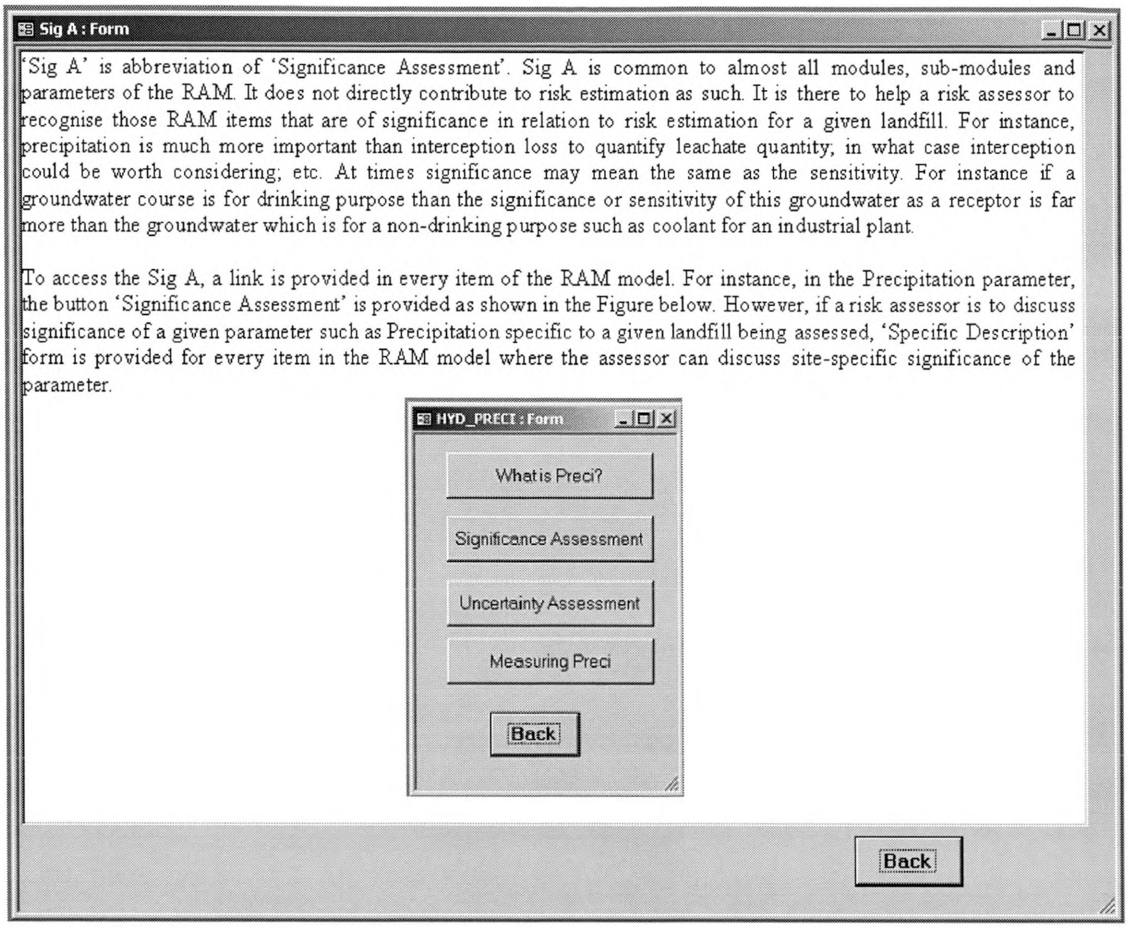
6.7 Significance Assessment (Sig A)

A click on the button Significance Assessment in the Main Front page of the RAM model (Figure 6.2), will lead the risk assessor to the form shown in Figure 6.29. This form describes the importance of the Significance Assessment in general perspective in the RAM model. This form can be accessed not only from the Main Front page of the RAM model but every module, sub-module and parameter of the model in order to render it handy for the user 'there and then'. This has been done by providing a 'Significance Assessment' link to each item of the model, as explained in Figure 6.29 with an example. The figure also explains that each item of the RAM model has been provided with a 'Specific Description' form as described in above sections of this chapter for various modules, sub-modules and parameters. For a given landfill being assessed, the risk assessor can discuss the site-specific aspects of the Sig A of a given RAM item in such a 'Specific Description' form specifically allocated for that RAM item.

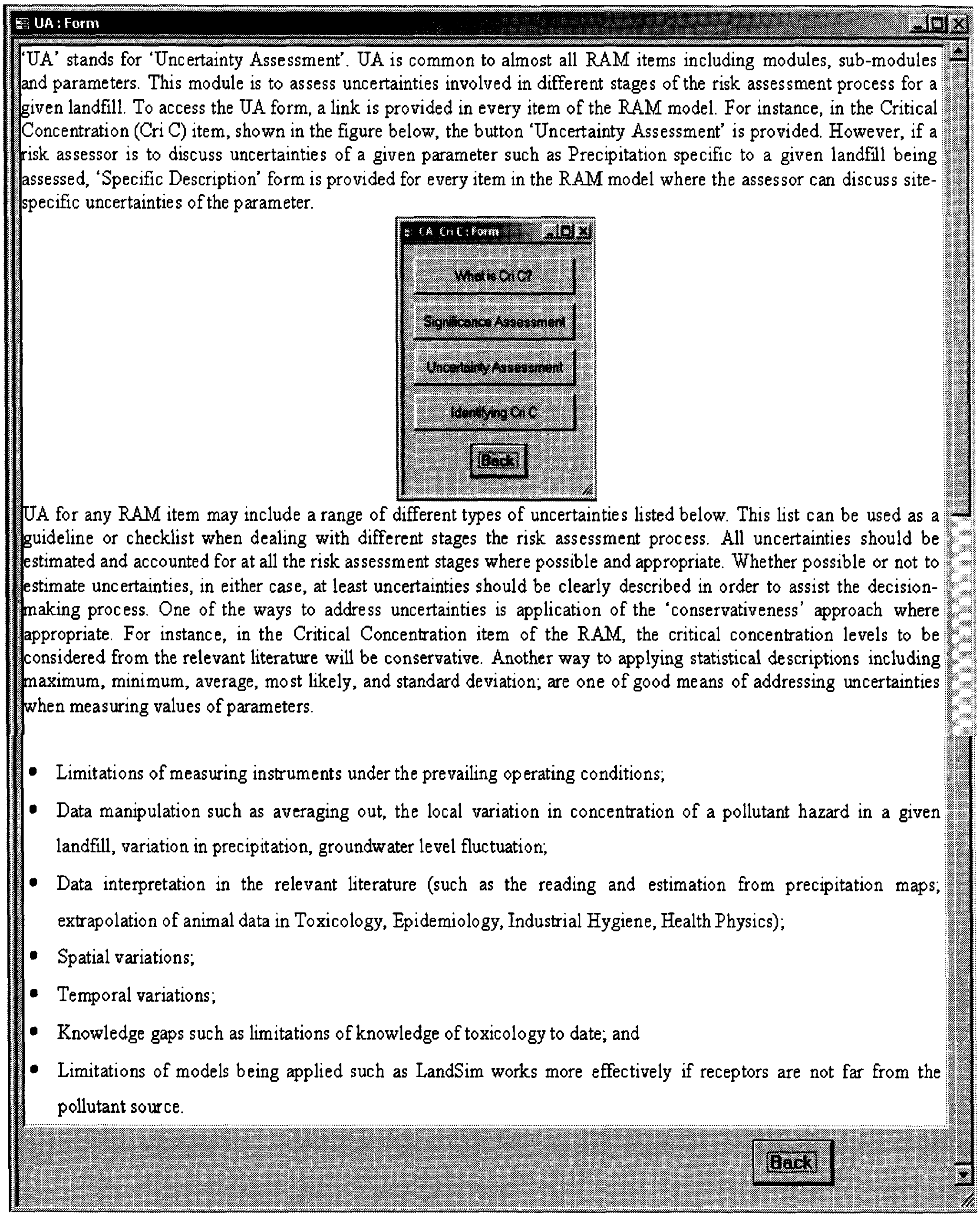
Figure 6.29: Significance Assessment (Sig A) Form in the RAM Model



6.8 Uncertainty Assessment (UA)

A click on the button Uncertainty Assessment in the Main Front page of the RAM model (Figure 6.2), will lead the risk assessor to the form shown in Figure 6.30. This form describes the importance of the Uncertainty Assessment in general perspective in the RAM model. This form can be accessed not only from the Main Front page of the RAM model but every module, sub-module and parameter of the model in order to render it readily available for the user. This has been done by providing an 'Uncertainty Assessment' link to each item of the model, as explained in Figure 6.30 with examples. The figure also explains that each item of the RAM model has been provided with a 'Specific Description' form as described in above sections of this chapter for various modules, sub-modules and parameters. For a given landfill being assessed, the risk assessor can discuss site-specific aspects of the UA of a given RAM item in such a 'Specific Description' form specifically allocated for that RAM item.

Figure 6.30: Uncertainty Assessment (UA) Form in the RAM Model



UA : Form

'UA' stands for 'Uncertainty Assessment'. UA is common to almost all RAM items including modules, sub-modules and parameters. This module is to assess uncertainties involved in different stages of the risk assessment process for a given landfill. To access the UA form, a link is provided in every item of the RAM model. For instance, in the Critical Concentration (Cri C) item, shown in the figure below, the button 'Uncertainty Assessment' is provided. However, if a risk assessor is to discuss uncertainties of a given parameter such as Precipitation specific to a given landfill being assessed, 'Specific Description' form is provided for every item in the RAM model where the assessor can discuss site-specific uncertainties of the parameter.

UA for any RAM item may include a range of different types of uncertainties listed below. This list can be used as a guideline or checklist when dealing with different stages the risk assessment process. All uncertainties should be estimated and accounted for at all the risk assessment stages where possible and appropriate. Whether possible or not to estimate uncertainties, in either case, at least uncertainties should be clearly described in order to assist the decision-making process. One of the ways to address uncertainties is application of the 'conservativeness' approach where appropriate. For instance, in the Critical Concentration item of the RAM, the critical concentration levels to be considered from the relevant literature will be conservative. Another way to applying statistical descriptions including maximum, minimum, average, most likely, and standard deviation; are one of good means of addressing uncertainties when measuring values of parameters.

- Limitations of measuring instruments under the prevailing operating conditions;
- Data manipulation such as averaging out, the local variation in concentration of a pollutant hazard in a given landfill, variation in precipitation, groundwater level fluctuation;
- Data interpretation in the relevant literature (such as the reading and estimation from precipitation maps; extrapolation of animal data in Toxicology, Epidemiology, Industrial Hygiene, Health Physics);
- Spatial variations;
- Temporal variations;
- Knowledge gaps such as limitations of knowledge of toxicology to date; and
- Limitations of models being applied such as LandSim works more effectively if receptors are not far from the pollutant source.

Back

6.9 Risk Characterisation (R Cha)

A click on the button 'Risk Characterisation (R Cha)' in the Main Front page of the RAM model (Figure 6.2), will lead the risk assessor to a form not shown here. In this form, the term risk is defined; quantitative and qualitative aspects are briefly explained; and the three modules branching out of the R Cha are indicated. This is provided as a quick on-hand reference to assist the risk assessor comprehend the way the R Cha structure works in the model. Once this form has been used, it can be closed.

In Figure 6.2, the link 'Hazard Indices (HI)' is to access the form shown in Figure 6.31. In this form, the button 'What is HI?' will pop open a form where some details have been set out on what HI is, its mathematical expression, and other implications are also pointed out with respect to the RAM. This form once benefited from can be closed. The links 'Significance Assessment' and 'Uncertainty Assessment' lead to discreet forms, which are similar as described earlier in this chapter for other RAM items. The link 'Measuring HI' in the form (Figure 6.31) leads to another form exhibited in Figure 6.32, which is discussed below. *The reader is recommended to pull up this form in the RAM model on a computer to see true colours (e.g. red, yellow, etc.) in the form, as these colours in Figure 6.32 will appear in various shades of grey being a black and white printout in this document.*

In order to execute the measuring of HI values, the form entitled 'HI_Measuring' and shown in Figure 6.32, is provided in the model. The button 'What specific Pathway and Target?' leads to a form where the risk assessor can record the given iteration or run of the RAM model being applied to which given environmental receptor and via which pathway. The RAM model has the limitation of considering one Target and Pathway combination at one time although with all possible hazards. Thus the Model needs to be applied or run repeatedly as many times as the number of pathway target combinations in a given landfill scenario being assessed. The HI itself is a dimensionless entity therefore does not have any units. However, the link 'Units' opens a form in case the risk assessor wants to mention units of HI numerator (TCf) and denominator (Cri C), thereby making sure that the units of the two items are the same. The link 'General

Description' is to access the form where the format and all functions of the HI_Measuring form (shown in Figure 6.32) are explained as a 'on-hand' help for the RAM model user. The 'Specific Description' link is to reach a form where the risk assessor can set out site-specific details regarding any worth mentioning aspects of hazard indices.

The Three Sets and The Nine HI Columns in the Table in the HI Measuring Form

In the table of the form 'HI_Measuring' there are three sets of columns one for Maximum, second for Mean or Most Likely (ML) and third for Minimum representing Worst Case Scenario, Most Likely Scenario and Least Bad Scenario, respectively. Each set contains three columns one for non-toxic hazards, second for carcinogenic hazards and third for non-carcinogenic hazards. Thus there are nine columns altogether covering Maximum, Mean / Most Likely and Minimum aspects for the three classes of hazards, i.e. non-toxic, carcinogenic and non-carcinogenic.

A button entitled 'HI Workout' is provided on the form (See Figure 6.32). This link when pressed runs a set of seven queries sitting in the computer programme behind the RAM model. These seven queries are to cover seven possible permutations of toxic, non-toxic, both toxic and non-toxic, carcinogenic, non-carcinogenic, and both carcinogenic and non-carcinogenic. The results thus calculated by the model or computer program automatically appear in the nine fields corresponding to all the quality hazards sitting in the first column. With the same operation results also appear spontaneously in the nine boxes of the THI row as well as the three grand THI totals (described below).

Note:
It must be noted that mean value of a given quality hazard (final) concentration should fall between maximum and minimum (final) concentrations of the quality hazard. Whereas in the RAM model, the corresponding Cri C value of the quality hazard is the same for all the three items, i.e. maximum, mean and minimum (final) concentrations. Thus, on comparison, when the three HI values are worked out, these should fall in the

same corresponding descending order. That is, the mean HI should neither be greater than the maximum HI nor less than the minimum HI. This also has been proved to be right in the assessment of the real landfill scenario in the model validation exercise for all the five quality hazards (Chapter 7). However, pH may or may not follow this rule being an exception as explained below.

Exception - HI interpretation for a quality hazard like pH

For a quality hazard like pH there is a limitation in the interpretation of HI value in the 'HI_Measuring' form in the RAM computer model and this is explained as follows. Generally, an HI value greater than unity means the concentration of a quality hazard (either pollutant or property) is beyond threshold and vice versa, which is correspondingly highlighted coloured (i.e. red) or not coloured (i.e. white). For the case of quality hazard pH, the model user will have to specially look out for HI value in the 'HI_Measuring' form and not rely on whether the HI value in the model is coloured (red) or not (i.e. white) otherwise it could be misleading. Similarly, also the concept of the 'total hazard index' does not apply to pH quality hazard and the model user will have to deal with it as a special case. This is because for the pH the value is ideally supposed to be 7.5 for the solution (e.g. surface water as a receptor). A value much greater or much less than either of these is not a good environmental characteristic implying that the solution either has more acidity or more alkalinity. Thus, pH value measuring 7.5 means the solution is not inclined to either of the two. Moreover, there may be a stretch or safety band across 7.5 optimum value to be used as a standard to measure pH against. This safety band may vary from scenario to scenario depending on what level of quality is set as a standard for a given environmental receptor (Baloch, 2007). For instance, in River Ecosystem Classification in the UK, the acceptable or standard pH range is 6.0 to 9.0 at the 95 percentile (Martin, 2007).

Total Hazard Index (THI) and Grand THI

At the bottom of each of the nine columns, there is a corresponding Total Hazard Index (THI) for each column (highlighted yellow). Thus THI is there for the three groups of hazards (i.e. non-toxic, carcinogenic and non-carcinogenic) at three different levels, i.e. Maximum, Mean or Most likely and Minimum. For instance, in the first set (which is regarding the Maximum scenario), the THI under the bottom of the first column (of the set) indicates Maximum THI for Non-toxic hazards only, which stands for Worst Case Scenario for the non-toxic hazards. Whereas at the bottom of the second and third columns of the same set, the THI values correspond to carcinogenic and non-carcinogenic hazards and yet for Maximum scenarios. Similarly in the second set (which is regarding Mean / Most Likely) the THI at the bottom of, for instance, the second column (of the set) indicates Mean or Most Likely THI for carcinogenic hazards only, where as the Mean / Most Likely THI is the representative of Mean / Most Likely Scenario for the carcinogenic hazards. The same principle holds for the rest of the columns in the three sets. A grand total for each of the three sets which are Worst Case, Most Likely and Least Bad Scenarios is also provided below the row of the nine THI values, as shown in the figure.

Objective of THI and Grand THI

If the risk assessor finds that the grand total HI for each of the three sets is below unity then there is no need to consider even the individual nine THI values. However, if any of the three grand THI totals are greater than or equal to unity, then the risk assessor needs to look into the individual nine THI values. For any of the nine columns, THI greater than unity means the risk assessor definitely has to reconsider the HI columns / fields in the HI_Measuring form to make sure looking at each row individually if there is any HI value greater than or equal to unity. These, however, would automatically be highlighted in red by the RAM model. These HI scenarios with greater than or equal to unity will need addressing, for instance, by applying risk control measures. Once these measures considered, the HI values in red should not appear red next time the RAM model is run. If some scenarios still appear red, then keep tightening the risk control measures until all the values in red do not appear red any longer (in which pH may be an exception). This THI concept can be extended further to the grand THI values. The principle remains the same but on a greater level, and again with the exception of pH quality hazard. For instance, if the grand THI (Maximum) value for the Worst Case scenario appears less than unity, then the individual three THI (Maximum) values for non-toxic, carcinogenic and non-carcinogenic quality hazards will automatically have to be less than unity, the former being the grand total of the latter three streams. The same holds for the grand THI (Mean) and grand THI (Minimum) scenarios.

Iterations

The whole risk assessment process carried out once up to the point of the THI values for Maximum, Mean and Minimum represents one specific landfill scenario of all specified hazards via a given pathway for a given environmental receptor / target. For the same or other hazards for the same or other targets via the same or other pathways the whole process from 'H Iden' to 'HI workout' will have to be repeated up to the point of THI values of the three sets. The number of iterations of the risk assessment process using this model will depend and be the same as the number of combinations of given pathways and targets.

As explained in Chapter 5, Section 5.9, if a given receptor is such as humans and mammals, the risk assessment process can be taken a step further to quantify risks if wanted by the risk assessor. For carcinogenic and non-carcinogenic scenarios the links entitled 'Carcinogenic Risks (R Carci)' and 'Non-carcinogenic Risks (R Non-carci)' are provided in the RAM model's Main Front Page form shown in Figure 6.2. These links open forms, which are similar in format to that shown in Figure 6.31 for Hazard Indices. The R Carci and R Non-carci forms contain mathematical equations, which the risk assessor can use, if appropriate, to quantify risks. These forms also possess Significance Assessment, Uncertainty Assessment, General Description and Specific Descriptions links in a similar pattern as other RAM items.

Figure 6.31: The Main Front Page / Menu of 'Hazard Indices (HI)' in the RAM Model

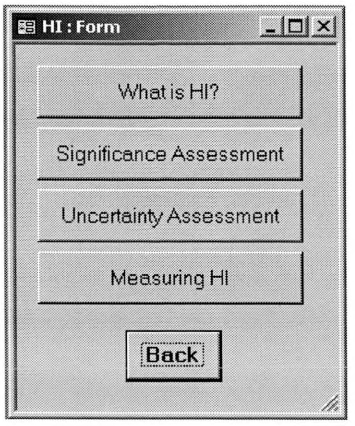
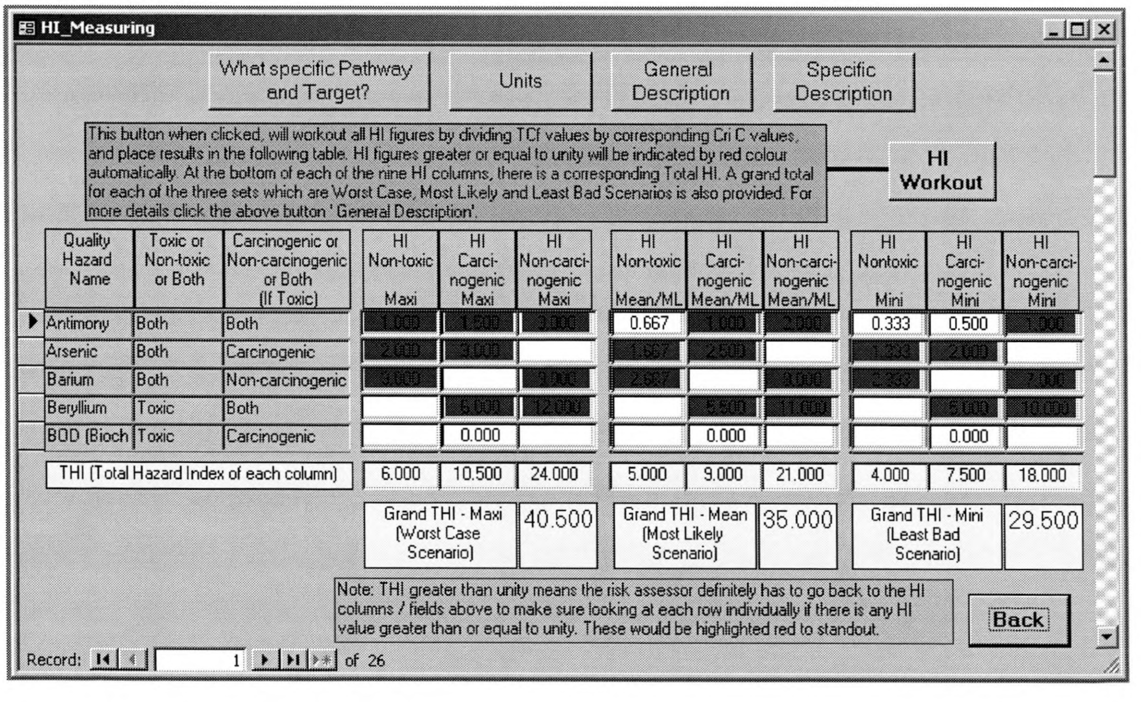


Figure 6:32: Measuring Form of 'Hazard Indices (HI)' in the RAM Model



6.10 Risk Reduction (RR)

In correspondence to Section 5.10 of Chapter 5, Risk Reduction (RR) is the second main part of Risk Management (RM). This is shown on the Front Main Page or Form of RAM model shown in Figure 6.2. As exhibited in the figure, the RR in the form branches out into a number of buttons or links such as Risk Evaluation (R Eva), Risk Control (R Cntrl), Consequences Evaluation (Conse Eva), Costs Evaluation (Costs Eva), Risk Monitoring (R Monit), Corrective Action. All these links or buttons are not hyper-active as these do not constitute the remit of the Risk Assessment but Risk Reduction, which is beyond the scope of the undertaking of this research study.

Chapter 7

VALIDATION OF THE RISK ASSESSMENT COMPUTER MODEL

This chapter is on a validation exercise of the computer model of the Risk Assessment Methodology (RAM) in which the model is applied to a real but anonymous landfill data confidentially provided by a company. The main focus of this validation stretches from Hazard Identification and Categorisation through Exposure Assessment and Concentration Assessment to Risk Characterisation in terms of Hazard Indices. The intent of the validation exercise is not the risk assessment results that this exercise will yield, but the process of risk assessment itself, which is considered throughout in two separate and parallel channels for comparison purposes. These two channels are the RAM model operation and the landfill assessment approach of the company.

7.1 The Scope of the Model Validation

In this chapter, the main emphasis of the validation exercise of the Risk Assessment Methodology (RAM) model is on how the RAM model operates in a real landfill scenario rather than on the results the validation exercise is to come up with. This is carried out below by highlighting differences between the format the RAM model suggests to conduct a landfill risk analysis in and ways landfills are assessed in the waste management industry. On the other hand, since there is an indefinite number of landfill scenarios and the model has been designed to be able to cope with any of them, it is not possible to find a single landfill which could validate each and every facet of the model. Moreover, the focus of the validation of the model are these RAM items (including their modules and sub-modules) which directly constitute the more crucial portion the RAM:

- Hazard Identification and Categorisation (H Iden),
- Exposure Assessment (Ex A),
- Concentration Assessment (CA), and
- Risk Characterisation (R Cha).

Another reason for the other RAM items not being as much the centre of the validation as the above listed ones is that they are not fully developed yet. These other items mainly comprise Baseline Study modules and sub-modules; a number of Migration Assessment modules and sub-modules; Uncertainty Assessment; and Significance Assessment.

7.2 Introduction to the Landfill Scenario for Validation

An anonymous but real landfill site in Scotland is considered for which an anonymous company has kindly provided data and information. The CD attached with this document manifests the functioning of the model with this landfill data. This manifestation file is named 'Model Validation'. The CD also contains excel sheets of the data in both organised format as well as crude or original form as were provided by the company. The title of the directory containing the data is called 'Landfill Data' and sub-directories of the two types of spreadsheets are 'Original Data' and 'Organised Data'. Prior to further discussion on how the data are analysed and organised; how and where the organised data are fed into the RA computer model; and how the model works with this data, some background information for the landfill is described below. Such background or preliminary information could be placed into the Baseline Study section of the model once fully developed in future. However, for now, this is quoted from reports on the landfill and narrated as below. From the point of view of quick and handy reference, readers of this document are advised to keep the 'Model Validation' file up and running side-by-side on a computer as the following discussion proceeds. *At the end of each section below, discrepancies between the approach applied by the company and the way RAM model operates are also described as being the aim of the validation exercise undertaken in this chapter. This way the chapter will also be able to identify how the company's landfill assessment approach could have been rendered* *more holistic. Another important point to be noted is that the landfill is being assessed for its current hydrogeological setting only due to brevity. That is, the current state of degree of contamination, hazards and risks are being assessed in this validation exercise and not the future state which may be different then the current situation.*

7.3 Baseline Study (BS)

The quarry in which the landfill is constructed was excavated into flaggy lacustrine sandstones of lower Devonian age. A north-east to south-west trending fault is a typical of major Middle Devonian tectonic structures. A rapid transition occurs from the south-west of the site moving eastwards from predominantly argillaceous deposits to an arenaceous sequence. It was concluded that the change in lithology was not attributable to the dip of the strata. Furthermore, a co-incident rapid change in ground water levels from approximately +140mAOD in the west to approximately +126mAOD in the east was noted. It was therefore concluded that there is a fault trending through the western part of the site, north-east to south-west parallel to the major fault to the east of the site. It was concluded that the fault has the effect of acting as a hydraulic barrier to groundwater flow, restricting eastward groundwater movement from the western side of the landfill. However, the groundwater on the other side of the fault generally flows to the east. Generally boreholes were drilled to 1m below base of landfill unless they intercepted discrete water bearing strata. However, the typical groundwater level is +142m AOD and the landfill base is +130m AOD.

Given the fine-grained nature of the sandstone, it is likely that the yield of groundwater would be low, and use for large-scale potable or industrial supply is unlikely. However, in one of the reports it has been stated that the groundwater discharges to an ordinary watercourse stretching on the north and east of the site. This watercourse is also used as a surface water sampling point. The approximate distance between the landfill and the watercourse is 900m. The watercourse is approximately 1m in width and 900mm in depth. The depth of the water running in the course is usually around 400mm, although can be more, up to 800mm deep, in rainfall.

The landfill commenced operations for the receipt of waste in 1994 and closed for the receipt of waste in 2003. However, the sampling of landfill leachate, groundwater and the surface watercourse runs nearly from the last quarter of the year 1995 upto the first quarter of the year 2006, which means approximately 10 years duration (See the Landfill Data Spreadsheets). Currently, the landfill is in post closure phase. Liners and capping have been applied to the landfill. The site has historically re-circulated leachate back into the site. However, the leachate has had to be tankered away with no re-circulation for some 18 months. Over the last 12 months on average 560m^3 leachate per month has been tankered off site. The tankering off is required to maintain leachate levels in the landfill body to comply with the licence.

Discrepancies:

There is more than one report, which contain preliminary information regarding the anonymous landfill site. However, none of them seem to have carried out a baseline study in the format as presented in the RAM model, that is, comprising the eight modules and their sub-modules. Therefore, in the context of preliminary investigation or baseline study, a summary from a number of reports regarding the landfill is laid down above. Due to the reasons mentioned earlier (Section 7.2), there is nothing fed into the Baseline Study portion of the 'Model Validation' file.

7.4 Hazard Identification and Categorisation (H Iden)

7.4.1 Leachate Quantity

The information on leachate quantity for the landfill is given by the landfill manager. Therefore, this falls in the category of methods of measurement called Organisation / Authentic Body. Therefore, on the Main Front Page of the RAM model (Figure 6.2, Chapter 6) the links from the 'H Iden' button are followed to the 'H Iden_Quantity_Measuring_Org' form. In the description field of the form the source of information is mentioned.

Following the guidelines in the 'General Description' form, the following site-specific information regarding the landfill is set out in the 'Specific Description' form accessible via the 'H Iden_Quantity_Measuring' form. Among the six categories of methods of measurement or estimation of leachate quantity, only one category has been selected, that is, Organisation / Authentic Body. Information for other categories' methods is not available. Moreover, the leachate quantity given is an average on a yearly basis. Neither maximum nor minimum values of leachate quantity are known, therefore the same mean value is taken as a maximum as well as a minimum. Therefore, when the button 'Workout' is pressed the RAM model runs a union query by bringing up the same mean value as the maximum and minimum values. It is also worth-noting that this is only the leachate quantity, which is tankered off the site. The amount of leachate that percolates down to become part of groundwater is not known. However, due to landfill liners this may safely be presumed to be a small amount, compared to the amount tankered away. This amount could be estimated using a water-budget approach between the parameters including precipitation, interception loss, transpiration, etc. However, complete information is not available on all of such aspects.

7.4.2 Leachate Qualities

On the Main Front Page of the RAM model the links from the 'H Iden' button are followed to access the 'H Iden_Quality_Identifying' form. The five considered quality hazards, identified from the landfill data provided by the company, are fed in this form of the model (See 'Model Validation' file). Once fed in this form these quality hazards will automatically be appearing in other relevant forms of the model as the risk analysis process proceeds further. These quality hazards are COD (Total), Ammoniacal Nitrogen, Chloride as Cl, pH and Electrical Conductivity. The leachate hazards are classified into properties and pollutants in the form's second column. However, with reference to Section 7.5.3 below, in the given landfill scenario the environmental receptor is non-living, i.e. a surface watercourse, which can not have toxic affects or catch cancer. Therefore, in the third column of the form all the five quality hazards are declared non-toxic. This discussion is also laid down in the 'Specific Description' form allocated to the 'H Iden_Quality_Identifying' form. *This can be noted that in the* *procured landfill data, even though the leachate contains a host of quality hazards but only five are chosen as these are the only ones considered in the environmental receptor, i.e. a surface watercourse by the company.*

7.4.3 Process and / or Layout Hazards

On the Main Front Page of the RAM model the links from the 'H Iden' button are followed to the 'H Iden_Process and / or Layout_Identifying' form. In this form of the model, eight links are provided for further forms of geology, hydrology, hydrogeology, topography, meteorology, geography, site management and human influences, in which process and / or layout hazards are indicated correspondingly as described below (see the 'Model Validation' file).

7.4.3.1 Geological process and / or layout hazards

The predominant geological material at the bottom of the landfill is sandstone which is substantially more permeable compared to earth materials such as clay. Thus, there is more risk of vertical migration of the leachate pollutants, comparatively.

7.4.3.2 Hydrological process and / or layout hazards

See below in the Hydrogeology section.

7.4.3.3 Hydrogeological process and / or layout hazards

The lowest groundwater level below the site is +126mAOD. So in comparison to the landfill bottom being +130mAOD, the depth of the unsaturated zone is a maximum of 4m. Nevertheless, the typical groundwater level being +142m AOD, there is typically no unsaturated zone to act as a sieve for the leachate, which is a very bad scenario in terms of enhancing the contamination rate and level.

The direction of the groundwater flow is towards the east and north-east of the site where the surface watercourse exists. Had the flow direction been away from the watercourse, the contamination risk would be lower.

7.4.3.4 Topographical process and / or layout hazards

There is a watercourse existing not far from the landfill, that is, about 900m away in the direction of north-east. This itself is a layout hazard, particularly when the groundwater is flowing towards the watercourse as well (See Section 7.4.3.3, above).

7.4.3.5 Meteorological process and / or layout hazards

There is enough rainfall / precipitation to produce enough leachate that a substantial amount of it has to be tankered off the site in order to keep on site leachate amount within a prescribed limit.

7.4.3.6 Geographical process and / or layout hazards

In comparison to many places in the world, Scotland is geographically situated on such a place on the globe where rainfall / precipitation is a very common phenomenon.

7.4.3.7 Site Management related process and / or layout hazards

Even though landfill liners and capping are applied to render the landfill system water tight, it is not possible to have a 100% water tight system, at least not for ever. Therefore, a safe and conservative approach is that the some degree of groundwater ingress into the landfill body may take place as the base of the landfill falls below the water-table in places. Similarly, despite the landfill capping, the precipitation may percolate into the landfill body to some extent at least. Irrespective of to what extent, the proof of both these phenomena likelihood is that there is enough leachate generated that it has to be tankered off the site.

7.4.3.8 Human Influence related process and / or layout hazards

There is little likelihood that groundwater would be yielded in large amounts due to the fine-grained nature of the sandstone. Also large-scale potable or industrial supply of this sandstone is unlikely. The water from the watercourse is also not known to be used for human consumption as such, though it is an amenity feature of the site. Thus, the amenity aspect of the watercourse is endangered.

7.4.4 Harms

On the Main Front Page of the RAM model the links from the 'H Iden' button are followed to the 'H Iden_Harm(s)_Identifying' form. This form contains further links for potential harms, which may come from the above three categories as explained below (see the 'Model Validation' file side-by-side).

7.4.4.1 Harms due to leachate quantity

One of the harms in the context of leachate quantity is that there is a substantial amount of leachate being generated to reach the groundwater or help migrate leachate pollutants to mix with the groundwater rendering it polluted. Moreover, the links on the pathway beyond the contaminated groundwater, including the surface watercourse, are also jeopardised in terms of environmental protection, as this contaminated groundwater migrates.

7.4.4.2 Harms due to leachate qualities

As indicated in Section 7.4.2 above, the leachate contains both hazard categories, that is, pollutants as well as properties. Due to these qualities the leachate has a potential to degrade, particularly the hydrosphere (comprising both groundwater as well as surface waters) below standards. In summary, the harm is environmental pollution of the watercourses and this is mentioned in the 'Harms' column of the H 'Iden_Quality_Identifying' form of the 'Model Validation' file.

7.4.4.3 Harms due to process and / or layout hazards

The process and / or layout hazards, which have been identified earlier (Section 7.4.3), are generating such a setting that has potential to render the water quality (both groundwater and surface water) below the environmental quality standards. This is what is referred to as harm or unwanted event due to process and / or layout hazards in the given landfill risk assessment scenario. This is elaborated with these examples. Since there is some degree of rainfall percolation and groundwater ingress into the landfill body, this contributes to generate even more landfill leachate. Consequently there is more chance of harm or an unwanted event, i.e. water quality to become poor. Over time when liners and capping degrade this harm may enhance even more. The watertable is above the landfill base at places, if not all the time then at least when the watertable rises above landfill base, which increases the harm or unwanted event of water pollution.

Discrepancies:

- The company approach does not contain Hazard Identification and Categorisation as presented in the RAM model. That is, there is no conscious categorisation into leachate quantity, leachate qualities, process and / or layout hazards, and harms.

- The approach to estimate landfill quantity applied at the given landfill by the company deviates from the way the RAM model suggests in the sense that it is not possible to establish worst case and least bad scenarios corresponding to maximum and minimum leachate quantities. This is because the given approach does not take account of maximum and minimum leachate quantity levels. Also the approach of six categories of methods of measurement not considered.

- Similarly there is no consideration of categorisation of leachate hazards into properties and pollutants as the RAM model does. There is no conscious consideration of the quality hazards in the context of non-toxic and also the justification of these not being toxic and carcinogenic is not given. In simple words, although not needed in the given scenario as such, the company approach does not seem to be aware that further classification into toxic, non-toxic, carcinogenic and non-carcinogenic groups was needed.

- The concept of process and / or layout hazards introduced in the RAM model, and as explained above, has not been applied in the company approach. The same holds for the 'harms' issue.

7.5 Exposure Assessment (Ex A)

7.5.1 Source Identification and Categorisation (Sorc Iden)

On the Main Front Page of the RAM model the links from the 'Ex A' button are followed to the 'Ex A_Sorc Iden_Identifying' form. In this form, via the 'Specific Description' button, a form is opened in which the following is recorded as information on the landfill as a source of contamination.

In the given environmental risk assessment scenario, the landfill, obviously, is a pollutant source. This is the only pollutant source as there is no other landfill or contamination source around to be considered as a combined adverse affect on the environment. The landfill is in the closed stage, is not taking any more waste, thus there are no more pollutants being added into the source. In other words, the landfill does not have any in-operation or pre-operation stages. The whole landfill is seen as a point source for simplicity. However, the exact location of this point or effective landfill body centre is not worked out due to lack of information on the landfill geometry.

7.5.2 Pathway Identification and Categorisation (P Iden)

On the Main Front Page of the RAM model the links from the 'Ex A' button are followed to the 'Ex A_P Iden_Identifying' form. In this form via the 'Specific Description' button a form is opened in which the following is recorded as the information on the pathway which is accounted for in this validation exercise.

The pathway in the given landfill risk assessment scenario comprises a number of media. The starting point of the pathway, that is the pollutant source itself, is the landfill in question and the end point is an environmental receptor mentioned in the 'Target Identification and Categorisation' module. On the basis of the information produced in the 'Baseline Study' and 'Process and / or Layout Hazards' sections, the unsaturated zone is available in places but not throughout the landfill base. To be conservative, therefore, it can be presumed that effectively there is no unsaturated zone, at least not throughout. Therefore, the only link between the source and the receptor is groundwater, which flows as an aquifer in the east and north-east directions. There is no specific information available on the aquifer, therefore no differentiation is made between the groundwater and the aquifer as such in this scenario.

7.5.3 Target Identification and Categorisation (T Iden)

On the Main Front Page of the RAM model the links from the 'Ex A' button are followed to the 'Ex A_T Iden_Identifying' form. For the giving landfill scenario there are no receptors or targets considered falling in the natural living and built environment categories, and this is also stated in the corresponding 'Specific Description' forms in the model. However, there is a non-living natural target, that is the surface watercourse located 900m form the landfill, as indicated in the Baseline Study section. This information is described in the 'Specific Description' form related to Non-living Natural Target(s) / Receptor(s) and fed into the table provided in the 'Ex A_T Iden_Identifying' form. Ideally, this information should be derived from the Topography module of the Baseline Study that can be reached via the 'Topography' button on the 'Ex A_T Iden_Identifying' form. However, since the Baseline Study section is not fully developed yet, as stated earlier, this information has not been derived from there electronically but 'manually' from the discussion in the Baseline Study section above. The same holds for the other seven buttons that correspond to the other seven modules of the Baseline Study of the RAM model.

7.5.4 Exposure Quantification (Ex Quan)

On the Main Front Page of the RAM model the links from the 'Ex A' button are followed to the 'Ex A_Ex Quan_Measuring' form. In this form the five quality hazards, which were identified in the H Iden section of the model, will automatically have appeared in the table. The button 'Units' leads to a form where the units of these quality hazards are stated. The unit for COD (Total), Ammoniacal Nitrogen, and Chloride is mg/l. The quality hazard pH has no unit being a dimensionless parameter and Electrical Conductivity's unit is uS/cm.

In this form via the 'Specific Description' button, a form is opened in which the following information is recorded along these lines. Since the environmental target is a watercourse (i.e. a non-living natural receptor), therefore the exposure routes ingestion, dermal contact and inhalation are not appropriate to use. Consequently, values for these three exposure routes are zero in the columns of the table in the 'Ex A_Ex Quan_Measuring' form. The only exposure route in this scenario suitable or applicable is 'Others if any', as the groundwater (contaminated by the landfill leachate) is found to simply enter the surface watercourse, as reported in the landfill assessment documents provided by the company. The values for maximum, mean and minimum Ex Quan come from the Ex MCf section (i.e. Exposure Medium Concentration – Final), which sits in the CA section of the model discussed below). To find these values in Ex MCf section and then put in this form, the link entitled 'CA_PC_Ex MCf_Measuring' provided at the bottom of the form is used. When the button 'Ex A_Ex Quan(t=ing+der+inh+oth)' on the form is pressed, a programme runs in the model and all the values in the columns of the table are summed, correspondingly to yield total maximum, total mean and total minimum values of quantified exposure as shown in the yellow highlighted fields in the table of the form. In this case, these values are the same as fed earlier in the corresponding three columns of the exposure route 'Others if any' because the remaining exposure routes are zeros by default as they do not apply.

Discrepancies:

- Unlike the RAM model, the company approach of the landfill assessment does not recognise the Exposure Assessment either as a complete section on its own or its necessary contributing modules and sub-modules.

- There is no discussion specific to source of contamination as described above. Moreover, no consideration is given to workout the effective geometric centre of the landfill body. However, this exercise has not been carried out in this validation exercise due to the lack of information about the landfill, as stated earlier.

- In the company approach, there is an absence of identification and categorisation of pathway(s) and pathway links in the format produced above.

- The company approach does not seem to have considered receptors / targets in the three categories as the RAM model suggests. Moreover, the eight module system of the Baseline Study, as presented by the RAM model via the corresponding eight buttons shown in the 'Ex A_T Iden_Identifying' form, is not applied in the company approach of landfill assessment. One simple reason for this is that the company approach has not and could not use a holistic computer model as it was not available.

- Unlike the way the model validation is explained above, the company approach does not appreciate Exposure Quantification as an entity in the landfill assessment. Probably, that is one of the reasons that the contaminated groundwater near the entry point to the surface watercourse has not been sampled to know the more exact picture. This point is explained more in the Ex MC module of the model validation (See Section 7.6.2.2 below).

7. 6 Concentration Assessment (CA)

7.6.1 Source Concentration Analysis (Sorc C)

On the Main Front Page of the RAM model the links from the 'CA' button are followed to the 'CA_Sorc_Measuring' form. Like the Ex Quan module above, in this form the five quality hazards, which were identified in the H Iden section of the model, will automatically have appeared in the table. The button 'Units' leads to a form where the units of these quality hazards are stated, which are to be the same as in the 'Units' form of 'Ex Quan' module earlier. *The 'Units' form is provided in each appropriate module and / or sub-module of the model with the idea of giving the landfill assessor an opportunity to make sure that units are kept the same all along the risk assessment process to avoid any miss-calculation. To avoid repetition, the 'Units' forms in the following stages of the risk analysis process will not be discussed.*

In the table of 'CA_Sorc_Measuring' form the concentrations of the same five quality hazards (above) are fed. These concentrations are worked out from the spreadsheet data on landfill leachate provided by the company. There is a wide range of quality hazards in the landfill leachate but only these five are chosen for the reason that the landfill company has considered only these five in the environmental receptor, i.e. surface watercourse. The Dissolved Oxygen (DO) even though considered in the environmental receptor is dropped from risk analysis process for these reasons. Firstly, it is a positive quality rather than a quality hazard and secondly, no threshold or benchmark has been found in SEPA (2005a) to use as standards to measure its concentration against. On the same form the button 'Specific Description' is clicked to open a separate form where the discussion in this paragraph has been recorded in the computer model.

7.6.2 Pathway Concentration Analysis (PC)

7.6.2.1 Pre-Exposure Medium Concentration Assessment (Pre-Ex MC)

On the Main Front Page of the RAM model the links from the 'CA' button are followed to the 'CA_PC_Pre Ex MC_Measuring' form. In this form via the 'Specific

Description' button a form is opened in which the following is recorded. With reference to Section 7.5.2 above, effectively there is only one link between the pollution source and the environmental receptor. This is the groundwater. Thus, in the given landfill scenario there does not exist any Pre-Exposure Medium but only the Exposure Medium discussed below.

7.6.2.2 Exposure Medium Concentration Assessment (Ex MC)

On the Main Front Page of the RAM model the links from the 'CA' button are followed to the three separate themes which are concentration analysis of quality hazards initial, reaching and final. For these three the corresponding forms are 'CA_PC_Ex MCi_Measuring', 'CA_PC_Ex MCr_Measuring', and 'CA_PC_Ex MCf_Measuring', respectively. In each of these forms, data are fed in along with the relevant explanations recorded in the corresponding 'Specific Description' forms. These relevant explanations are also laid down as follows:

The landfill company has taken groundwater samples in the immediate vicinity of the landfill to establish the degree of contamination into the groundwater off the landfill (See the Landfill Leachate Spreadsheet in the Landfill Data). However, this is not pursued up to the environmental receptor. That is, no sampling is performed in the immediate vicinity of the surface watercourse neither to establish how this contamination degree attenuates by the time the contaminated groundwater is entering the surface watercourse nor to work out what were the background concentrations of the quality hazards before the contamination reached there. The only benefit of knowing the concentrations of the quality hazards in the groundwater immediately around the landfill is the achievement of the reassurance that landfill has contributed and is contributing in contaminating the groundwater, which is the Exposure Medium i.e. Ex MC.

As stated above, since there are no concentration values of the quality hazards available for the groundwater just before it enters the surface watercourse, an assumption has to be made in this model validation as follows. The concentrations of the quality hazard in the groundwater near the surface watercourse is assumed to be the same as in the surface watercourse (discussed below) by ignoring the dilution within the surface watercourse and other hydraulics / fluid mechanics factors that may be engaged when groundwater enters the surface watercourse. Ideally, as per the RAM model format, groundwater samples near the surface watercourse should have been taken from 10 years ago until recently. This is in order to establish a more exact picture of the concentrations of the quality hazards by rendering it possible to engage the temporal and spatial philosophy of Exposure Medium Concentration Initial or Background (Ex MCi), Exposure Medium Concentration Reaching (Ex MCr) and Exposure Medium Concentration Final (Ex MCf). However, the landfill company has neither applied this approach nor has enough data both spatially and temporally to let the computer model engage with this philosophy. Therefore, for Ex MCi the assumption is that background concentrations in the groundwater near the surface watercourse are or were approximately zero, reaching concentrations are the same as the final which again have already been assumed to be the same as in the surface watercourse, as explained earlier.

It should be noted that the button or link 'Migra A_Ex MCr_Measuring' on the 'CA_PC_Ex MCr_Measuring' form is not useable in this scenario of landfill risk analysis. The reason is that in this case the information does not come from the Migra A section of the model, but is derived from the assumption that the concentrations of the quality hazards reaching the exposure medium are approximately the same as the concentrations in the surface watercourse. In other words these values have simply come from the samples taken from the site.

7.6.3 Target Concentration Analysis (TC)

On the Main Front Page of the RAM model the links from the 'CA' button are followed to the three separate themes which are concentration analysis of quality hazards initial, intake and final. For these three the corresponding forms are 'CA_TC_TCi_Measuring', 'CA_TC_Intk C_Measuring', and 'CA_TC_TCf_Measuring', respectively. In each of these forms data are fed in along with the relevant explanations recorded in the corresponding 'Specific Description' forms. These relevant explanations are also laid down as follows:

The landfill company has taken surface watercourse samples not upstream but mainly along where the groundwater meets the watercourse to establish the degree of contamination in the surface water (See the Surface Water Spreadsheet in the Landfill Data). However, since the samples are not taken upstream, it is not possible to establish the background concentrations of the quality hazards in the surface water. Therefore it is assumed that the quality of the surface water before it meets the leachate contaminated groundwater is approximately pure, i.e. zero background concentrations of the quality hazards.

Ideally the surface water samples should have been taken from upstream for TCi from 10 years ago until recently. This is in order to establish a more exact picture of the concentrations of the quality hazards by rendering it possible to engage the temporal and spatial philosophy of Target Concentration Initial or Background (TCi), Target Concentration Intake (Intk TC) and Target Concentration Final (Ex MCf). However, the landfill company has neither applied this approach nor has enough data both spatially and temporally to let the computer model engage this philosophy. Therefore, since TCi values are assumed to be approximately zero, intake concentrations by the surface water are the same as the final concentration in the surface watercourse.

The Risk Assessment Methodology states that concentrations of quality hazards that an environmental receptor takes (i.e. Intk C) are measured in the form of Exposure Quantification (Ex Quan). Following this principle the Intk C values, which the surface watercourse receives from the leachate contaminated groundwater, were measured or established in the form of 'Ex Quan'. These Ex Quan values are imported from the 'Ex A_Ex Quan_Measuring' form into the 'CA_TC_Intk C_Measuring' form. Since TCi values are assumed to be zero and only Intk C values are known, therefore even if a mass balance approach is applied literally, the TCf values are to turn out to be same as Intk C values. Thus, the Intk C values are placed in the 'CA_TC_TCf_Measuring' form as TCf.

7.6.4 Critical Concentrations (Cri C)

The Critical Concentration values are predominantly taken from Schedule 2, Appendix

II of the publication SEPA, 2005a. The term Environmental Quality Standards is used for Cri C in the publication. The Cri C values are 0.5 mg/l, 250 mg/l and 2500 uS/cm (at 20^{o}C) for Ammoniacal Nitrogen, Chloride and Electrical Conductivity, respectively. Since the publication does not seem to set standards for pH and COC (Total), as a fall-back position advice was sought from experts in the industry as follows. Ideally the pH value should be 7.5, though as an environmental quality standard it may vary from 6 to 9 depending on the characteristics of a scenario (Baloch, 2007). In the landfill assessment in question this is taken to be 7.5, i.e. the ideal Cri C value, as the surface watercourse is a freshwater scenario. There is a relationship between Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), that is, the latter is generally twice as much as the former (Martin, 2007). From the point of view of Cri C, the COD (Total) is set to be 125 mg/l (Baloch, 2007).

On the Main Front Page of the RAM model the links from the 'CA' button are followed to the 'CA_Cri C_Identifying' form. The five quality hazards will already be found sitting in the first field of the table in the form. This is worth noting since the environmental receptor is non-living (as stated earlier), toxicity and carcinogenicity are not the issue. Therefore, the second column already shows 'non-toxic' for all the five quality hazards in the form where as the third column is already appearing blank from the H Iden_Quality module. The Cri C values established above are simply placed in the fourth field, entitled Cri C Non-toxic, of the table in the form. The summary of this discussion is put in the 'Specific Description' form, which is accessed via a link provided on the 'CA_Cri C_Identifying' form.

Discrepancies:

- Contrary to the RAM model format, the landfill assessment approach of the company neither acknowledges the Concentration Assessment as an overall unit in itself nor does its important constituting modules and sub-modules.

- With reference to the Section 7.6.2.1 above, not in parallel with the format of the RAM model, the company approach does not seem to strategically analyse the status of the media or links between the landfill (i.e. the pollutant source) the environmental receptor, i.e. the surface watercourse. That is no consideration of the Pre-Ex MC concept.

- Similarly, with reference to the Section 7.6.2.2 above, unlike the RAM model style, the company approach does not categorise data collection and organisation in the groups of initial, reaching and final concentrations of the quality hazards, i.e. Ex MCi, Ex MCr, and Ex MCf. Thereby, it not possible to consider a mass balance approach and temporal and spatial variations to establish more true picture of the concentration of the quality hazards in the exposure medium.

- With reference to the Section 7.6.3 above, not in parallel with the format of the RAM model, the company approach does not seem to strategically analyse the status of the environmental receptor or target. The company approach does not collect data on surface water quality classifying along the themes of initial, intake and final concentrations of the quality hazards, i.e. TCi, Intk C, and TCf. Thereby, it not possible to consider a mass balance approach and temporal and spatial variations to establish more true picture of the concentrations of the hazards in the body of the target.

- Although the reports on the company approach of the landfill assessment seem to mention environmental standards to a point, but not as detailed and transparent as the discussion laid down above in Section 7.6.4. For instance, the company approach lacks information on how to decide a pH value as an environmental standard when the publication SPEA (2005a) does not clearly recommend it for freshwaters; explanation on why BOD is not included in the company approach; describing why there is no significance of toxicity and carcinogenicity in the given landfill scenario; etc.

7.7 Migration Assessment (Migra A)

On the Main Front Page of the RAM model the links from the 'Migra A' button are followed to the 'Migra A_Ex MCr_Measuring' form. In the given landfill scenario a fate and transport software or e.g. LandSim model have not been applied, as the concentrations are directly measured on the basis of the samples collected from the site. Therefore, the probability in the given scenario is unity or 100% as the concentrations reflected by the samples have definitely reached the exposure medium. In other words there is no uncertainty about that. Thus, the number '1' is fed in the probability field (i.e. the last field) of the table in the form corresponding to each of the five quality hazards. With reference to the Section 7.6.2.2 (last paragraph), the values of Ex MCr need not be placed in the table of the 'Migra A_Ex MCr_Measuring' form. However, these will automatically appear in this table. The reason is the automatic electronic connection between the table of this form and that of 'CA_PC_Ex MCr_Measuring' form.

Discrepancies:

The company approach does not recognise the probability aspect. With reference to the holistic format presented in this research study, the Migra A is not consciously appreciated either in the context of its position in the risk analysis or even as a factor of the risk assessment. For example, there is no consideration given to the 'Ex MCr' at the point where the leachate polluted water meets the surface watercourse.

7.8 Significance Assessment and Uncertainty Assessment

These aspects specific to the given landfill scenario are covered throughout the process of risk analysis on an item by item basis. This is done by touching on these aspects in the corresponding 'Specific Description' forms of the RAM items where appropriate.

Discrepancies:

The company approach towards the risk assessment appears to be oblivious to the existence of Significance Assessment as well as Uncertainty Assessment in general. Speaking more site-specifically, the company approach has not given a consideration to these entities on an item by item basis as done in the RAM approach.

7.9 Risk Characterisation (R Cha)

The modules on Carcinogenic Risks and Non-carcinogenic Risks are of no significance in this risk assessment as the given environmental receptor is a non-living target. However, the Hazard Indices module is applicable in this scenario. On the Main Front Page of the RAM model the links from the 'HI' button are followed to the 'HI_Measuring' form. Using the link 'What specific Pathway and Target?' a form is opened in which the following is stated. This iteration of working out hazard indices is for this set of pathway and target. The pathway comprises landfill leachate, via the medium i.e. the groundwater to the target i.e. the surface watercourse.

As stated earlier (in Section 7.5.3), the environmental receptor is non-living, therefore toxicity and carcinogenicity are not the issue. Consequently, in the table in the 'HI_Measuring' form the second column already shows 'Non-toxic' and the third columns is already appearing blank from the H Iden_Quality module. When the button 'HI Workout' on the form is pressed, the model will run a set of 'queries' designed in the developed computer programme (details in Chapter 6). The HI values thus calculated appear only in the three Non-toxic columns of the table in the form, i.e. HI Non-toxic Maximum, HI Non-toxic Mean and HI Non-toxic Minimum. The other six fields of HI values (regarding carcinogens and non-carcinogens) are to appear blank. Correspondingly, the results also spontaneously appear in the THI and Grand THI totals. The interpretation of these results is stated below and a summary is narrated in the 'Specific Description' form that can be accessed via a link with the same name on the HI_Measuring form.

In the Grand THI row in the 'HI_Measuring' form, the Grand THI (Minimum) value is less than unity. That implies that none of the individual HI value is greater than unity, depicting no red colour. HI being the indicator of risk, this implies that there is no indication of risk from any quality hazard for the 'least bad' scenario. However, pH being an exceptional case, has to be considered individually and separately. The HI (Minimum) value is 0.712 which means 0.712 x 7.5 = 5.34. This falls outside the safe range of 6.0 to 9.0. Thus the HI value in case of pH indicates a risk of imbalance between acidity and alkalinity. A control measure to fix this will be required to render the surface water environmentally friendly even for the least bad scenario.

The Grand THI (Mean) value is greater than unity, therefore the THI (Mean) is examined as well, which in this case is the same as the Grand THI, as there are no HI values for carcinogenic and non-carcinogenic but only non-toxic. Since, the THI value is also greater than one (for the non-toxic field), therefore we search the individual HI values and find that the HI value is greater than unity for Ammoniacal Nitrogen, as the automatic red colouring by the RAM model's computer programme also depicts so. Except pH, this implies the Ammoniacal Nitrogen pollutant offers risk which is not acceptable according to the standards laid down in SEPA (2005a). This is for the most likely scenario and a risk control measure will be required. pH being an exception is considered discretely again. The HI value for pH = 0.933, which is approximately equal to unity. This implies that pH value is nearly 7.5, which is ideal. Hence, except for ammoniacal-nitrogen, all the quality hazards are within safe levels for the most likely risk scenario.

The Grand THI (Maximum) value is greater than unity, therefore the THI (Maximum) is examined as well, which in this case is the same as the corresponding Grand THI, as there are no HI values for carcinogenic and non-carcinogenic but only non-toxic. Since, the THI value is also greater than one (for the non-toxic field), therefore we search the individual HI values and find that the HI value is greater than unity for all the five quality hazards, as the automatic red colouring by the RAM model's computer programme also depicts so. Except pH, this implies the quality hazards offer risk which is not acceptable according to the standards laid down in SEPA (2005a). This is for the worst case scenario and a risk control measure will be required. The pH quality hazard being an exception is considered discretely again. The HI value for pH = 1.173, which means 1.173 x 7.5 = 8.8. This implies that the pH value falls within the standard band, i.e. 6 to 9, and is therefore safe.

Note:

With reference to the Note in Section 6.9 of Chapter 6, this can be and must be recognised that the worst case scenario should be worse than the most likely scenario. The model validation proves this by showing that the HI values of the former are greater than those of the latter. Similarly, the least bad scenario should be better than the most likely scenario. This is also illustrated by the validation exercise, as the HI values of the former are less than the latter. In simple words, HI values of mean / most likely scenario must fall between those of worst case and least bad scenario as the RAM model validation has also shown. However, pH is always an exception.

Discrepancies:

- Hazard indices for carcinogens and non-carcinogens are not applicable in the given landfill scenario but the company approach is definitely unaware of this concept.

- Unlike the RAM format, the company approach is not minded to clearly state which pathway and target combination is being considered (for the set of the five quality hazards) in the given iteration of the landfill assessment.

- The concept of Hazard Indices as developed in the RAM model is simply not applied as clearly as depicted in the above model validation exercise, e.g. the 9 columns in the 'HI_Measuring' form.

- The concept of maximum, mean and minimum corresponding to worst case, most likely and least bad risk scenarios, respectively, is not employed in the company approach.

7.10 Overall Discrepancies between the RAM and Industry approaches

Ideally, the validation of the RAM model should have been carried out with data sets from more than one real landfill. This is to better establish the nature and extent of discrepancies, as well as the degree of variation amongst discrepancies, between RAM and industry approaches to risk analyses of landfill sites. However, given the scope of the project, it was not possible to use data sets from more than one landfill. This deficiency was met indirectly in the following ways. Staff members from various relevant organisations in industry were contacted to enquire if there is any holistic landfill risk analysis approach of the degree presented in the study. These organisations include the Scottish Environment Protection Agency (SEPA), ENVIRON (United States), Saracen Environmental Services, Shanks Waste Solutions, Wessex Water (England), Be Environmental Ltd., Environmental Leadership Ltd., Chartered Institute of Waste Management (CIWM), North West Regional Assessment Centre (England), Biffa Waste Services Ltd., Peter Brett Associates, Environment Agency, and various district and city councils. No evidence of a holistic risk assessment approach, such as presented in this study, was found to exist at any of these organisations. Furthermore, the model validation and the interviews with various organisations related to waste management were underpinned with a detailed review of literature and computer models employed in industry (see Chapters 3 and 4). Another concrete evidence is presented via the publication of six international peer reviewed journal articles and two conference papers out of this study (See page iii).

The validation of the computer model has been carried out in this chapter mainly by drawing comparisons and identifying differences between the way RAM model recommends a holistic risk assessment should be carried out and the way company has carried this assessment out in the real world. For the given real landfill data employed in the model validation, the landfill company's approach towards landfill risk assessment is found not to be a complete risk analysis. The company's approach lacks various elements and characteristics of the RAM model, e.g. sequence, holistic nature, user-friendly format, algorithms, categorisations, background concentrations, and rich information. Although the company's approach contains a number of risk analysis aspects, it is not a holistic approach. The validation exercise and the direct consultation with the various waste management organisations suggest that the outcome from the model validation on the given landfill has yielded results similar to other landfill scenarios that are assessed in industry.

Chapter 8

CONCLUDING REMARKS

This chapter concludes the research work undertaken. It encompasses both outputs as well as outcomes of the research. It draws on novel aspects of the study as well as indicating future research potential, which this study has brought about. The development of a holistic framework of the Risk Assessment Methodology (RAM) along with the computer model generation is regarded as the overall original addition to the existing knowledge. Then the chapter leads to how knowledge is generated on the individual constituents of the methodology referring to them as RAM items. There is also a section specifically drawing on the attributes of the RAM computer model. After discussing these outputs of the research project, the chapter moves on to narrate expected benefits and further research potentials that have come out of the project as prompts and means for knowledge generations in the future.

8.1 The Overall Novel Aspect

Landfills continue to be the most predominant method of waste disposal particularly in the UK and generally elsewhere despite their relatively high potential to pollute the environment. Therefore risk assessment is required as a tool to combat landfill hazards in favour of the environment. The risk assessment is the most important factor for an effective risk reduction / control, as the degree of success of the latter is based on the former. Risk assessment and management is the best possible approach to assist in drawing an effective compromise between pollution potential and necessity of landfills so that the philosophy of sustainable development is adhered to.

On the other hand such a quantitative risk assessment methodology or computer model does not exist for landfill leachate in a holistic format, which could help perform the process of risk assessment from the start (i.e. baseline study) through to the end (i.e. hazard indices and risk quantification). In this research study, an integrated framework of such a methodology is presented. Furthermore, this methodology is quantitative and also translated into a corresponding computer model, which is tested and validated. The holistic framework and computer model of the RAM clearly establish and integrate all parts and sub-parts of the risk analysis process in an algorithmic and categorical manner. The RAM model also indicates how, when and where outputs of different modules and sub-modules of a given risk assessment process are inputs to other modules and sub-modules. Thus, the framework maps the mutual information transfer both backwards and forwards among sections and sub-sections of the RAM. The methodology and its model also established a relationship between hazard assessment, risk estimation, risk analysis, risk reduction, and risk management as a superset in housing them all. *The development of the holistic framework (Figure 5.1), the RAM and the corresponding computer model (which also embeds the HAM i.e. Hazard Assessment Methodology) are the overall novel aspects of the research work.*

This novel work may assist in the communication of risks of a given landfill to a much wider community addressing both technical and non-technical stakeholders, which has not been possible effectively until now. This work, particularly due to the incorporation of features of transparency and consistency, will help with a more integrated risk assessment and management of landfills not only as individuals but also at the collective level in terms of drawing comparisons and establishing which landfill scenario is least risky than others. This is due to the RAM has potential to introduce uniformity. The novelty of the work is further demonstrated by the publication of **six** international peer reviewed journal articles and two conference papers from the PhD work (see page iv).

8.2 The Risk Assessment Items

In the light of the review of literature and computer models to date regarding risk assessment in general and concerning landfills in particular, knowledge gaps were identified. These gaps were transformed into a 'wish list' in the form of aims and objectives in order to establish which of the knowledge gaps are to be attempted to bridge. This 'bridging exercise' included adopting, adapting and furthering existing risk assessment practices and research works, and even generating knowledge in order to enable the research study to assemble various risk assessment parts, sub-parts, modules, sub-modules and parameters from the perspective of landfill leachate. The 'bridging blocks' manufactured in this undertaking are referred to as 'other novel aspects' and described below. All these building blocks were assembled together to construct a more holistic RAM and the model already mentioned in the above section as the 'overall novel aspect' of this research study. Moreover, these RAM items or building blocks are designed to be holistic within themselves as individuals to address wide ranging landfill systems and scenarios as described below.

8.2.1 Baseline Study

This research study develops a holistic framework of an integrated and quantitative Baseline Study procedure comprising wide-ranging modules, sub-modules and parameters. The procedure is also transformed into a computer model, which is a part of the total RAM model. These are eight modules which include geology, hydrology, hydrogeology, meteorology, topography, geography, site management, human influence. In the literature review of risk assessment methodologies and computer models no evidence has been found on the procedure of the collection, organisation and analysis or collation of data on the Baseline Study modules (above). This research project has bridged this knowledge gap.

8.2.2 Hazard Identification and Categorisation

No procedure for Hazard Identification and Categorisation has been found in the literature review to date either in risk assessment methodologies or computer models for landfills. This research study addresses this knowledge gap by developing a holistic framework of an integrated procedure for Hazard Identification and Categorisation. This consists of four modules including Leachate Quantity, Leachate Qualities (both Pollutants and Properties), Process and / or Layout Hazards and Harms. In this way the methodology expands the conventional boundaries of a hazard from being a substance only to hazards due to leachate quantity, process and layout factors. The procedure is also transformed into a computer model, which is a part of the total Risk Assessment Methodology (RAM) model.

8.2.3 Exposure Assessment

A large amount of literature is available on the exposure analyses. However, none of them is purely and strictly from the point of view of landfill risk assessment. No such computer model of exposure assessment has been found either. This research project adapts the available literature on exposure assessment in terms of landfill risk assessment and produces a procedure with a corresponding computer model. Like other risk assessment factors, the total RAM model also embeds this computational Exposure Assessment method. In order to apply a holistic approach, the Exposure Assessment section of the RAM comprises Source Identification and Categorisation, Pathway Identification and Categorisation, Receptor / Target Identification and Categorisation, and Exposure Quantification which covers exposure routes for whole range of living as well as non-living receptors.

8.2.4 Concentration Assessment

Some literature is available on the issue of concentrations of hazards. However, none has been found describing how to holistically establish hazard concentrations in a categorical manner such that other parts of risk assessment could be related to at different stages of the risk analysis process as appropriate. In this research work, the concept of toxicity assessment is expanded in order to accommodate other important aspects. Thus, in this study, Concentration Assessment is set out in the form of a procedure, which consists of Source Concentration Assessment, Pathway Concentration Assessment, Receptor / Target Concentration Assessment, and Critical Concentration Assessment (which also includes 'toxicity assessment' feature). These four modules are further categorised into sub-modules to capture other features of hazard concentration analysis such as initial or background concentrations in exposure media and receptors. No evidence of a computer model, which contains these modules and sub-modules, has been discovered. This research project covers Concentration Assessment in the form of a procedure as well as a corresponding computer model, which constitutes the total RAM model.

8.2.5 Hazard Assessment

In this research study Hazard Assessment item has been produced as a separate entity in its own right, rather than just as a part of the risk assessment and management. Thus, a holistic approach along with computerisation has been developed for the quantitative Hazard Assessment alone from the specific perspective of landfill leachate. This task has been accomplished by developing and weaving together the above four sections of the RAM, which are Baseline Study; Hazard Identification and Categorisation; Exposure Assessment and Concentration Assessment. However, the Hazard Assessment has been designed in such a way that when applied to a landfill scenario, its results will be readily available to tap into the Risk Estimation stage to complete the whole of the risk analysis process. In the review of literature to date and current computer models, no such attempt has been discovered for landfill leachate. Thus, this work in its own right is a novel feature of the research project undertaken.

8.2.6 Migration Assessment

Although this item has not been developed in this study to any great detail, designing its overall structure; classification of its modules and sub-modules; identifying its place in the RAM; and establishing its relationships with other RAM items are amongst a few facets explored. Migration Assessment framework has not been prepared only as a part of the overall methodology (RAM) but also translated into the corresponding computer model. No evidence was found of the Migration Analysis in the review of literature and computer models being recognised as a discreet item of a risk assessment process. In this research work, the Migration Assessment has been given a clear place in the RAM and correspondingly in the RAM computer model.

8.2.7 Significance Assessment

The existence of the Significance Assessment aspect has been discovered in the literature review. However, no literature seems to have put the Significance Assessment into perspective for each risk analysis item. Similarly, in the investigation of computer models the Significance Assessment is not found integrated as a crucial part of every risk assessment item at individual level. This research study has established the relationship between the Significance Assessment and all RAM items in the computer model explaining its context with examples. Also, there is a specific form provided in the model for each RAM item, where the risk assessor can describe the site-specific Significance Assessment of the item. However, the Significance Assessment section of the RAM has not yet been developed to great detail.

8.2.8 Uncertainty Assessment

The status of the Uncertainty Assessment is not discovered to be different from that of the Significance Assessment in the literature review. Similarly, the Uncertainty Assessment aspect has been addressed along the same lines in the research undertaken as explained above for the Significance Assessment.

8.2.9 Risk Characterisation

Generally in the literature the concept of hazard index is related to non-carcinogens and that of risk quantification to carcinogens. Thus, both notions are mainly regarding living receptors only. The hazard index approach has been widened in this research study to address both living and non-living environmental receptors. Moreover, both notions, that is, the hazard index approach as well as risk quantification have also been expanded to cover both carcinogenic and non-carcinogenic hazards. This is summarised below. Thus, the Risk Characterisation part of the RAM has been divided into three modules which are Hazard Indices (HI); Risk Carcinogenic (R Carci); and Risk Non-carcinogenic (R Non-carci). These three modules of Risk Characterisation have also been translated into computer modelling.

- the hazard index concept is applied to both living and non-living receptors;
- the hazard index approach is developed to engage both carcinogenic and non-carcinogenic scenarios; and
- the risk quantification approach is applied to both carcinogenic and non-carcinogenic scenarios.

8.3 The RAM Computer Model

All the parts, sub-parts, modules, sub-modules, and parameters of risk assessment mentioned above, once prepared individually were assembled together to form a holistic methodology of risk analysis. This methodology was later converted into a corresponding electronic presentation, that is, a knowledge-based computer model which is more readily useable than would be a simply documented procedure. The computer model, in addition to encapsulating the RAM items above also has the novel features (listed below) to ease the model running whilst enhancing the model's use for risk assessors and managers.

Despite huge variations in nature, size and function of various factors of the methodology, the format of all modules, sub-modules and parameters of the model have been developed in a similar pattern to the possible best degree in order to render the model smoothly and conveniently useable by the users. Furthermore, the idea is to ease not only the mutual information transfer between modules and sub-modules but also the traceability or tractability of any module, sub-module, parameter, information and data in the structure of the methodology model, i.e. easy manoeuvring within the RAM software model as well as within the simulated / applied model. Also, where appropriate, the mutual data and / or information transfer amongst the modules and sub-modules of the RAM model is designed to take place automatically. The model contains the features (listed below) which also reflect on the ability to cope with various landfill systems and scenarios.

- Can explicitly take into consideration existing and future environmental legislation and statutory instruments;

- Can provide results not only in transparent but also consistent format thereby making it feasible to compare estimated risks between different landfills, which can also assist in siting a landfill where environmental risks are relatively low;

- Can bring out more clearly at what stages of the risk assessment process of a given landfill, what and why assumptions are made and where uncertainties are. In other words, rendering the risk assessment more transparent (as shown in Chapter 7 on the RAM Model Validation);

- Contains an 'upgradibility' feature. This is explained with this example. The sciences including toxicology, health physics, and epidemiology, do not provide complete information about all hazards in terms of Critical Concentrations for different targets, particularly, for the living receptors. Thus, there is room for updating Critical Concentration section in the model being flexible enough to take new environmental standards on board.

- Delivers increased accuracy and performance;

- User friendly, self-guiding in the form of dialogue boxes, and quicker to learn and understand, and easy to use. In other words, promotes user friendliness and operation simplicity;

- Enhances flexibility, usability, inter-portability and inter-operability;

- Mutual interconnections between various RAM items via corresponding links where appropriate, for instance, 'Significance Assessment in general' button in the 'Hyd_Preci_Sig A' form connects 'Sig A' section of the RAM Model; connection between Ex MCf and CA forms.

- Spontaneous or automatic mutual information transport between various RAM items, for instance, the H Iden_Quality module automatically transfers or displays all identified 'quality' hazards on other relevant modules and sub-modules such as 'HI_Measuiring' form.

- External portability, that is very receptive to external database, for instance, List 1 and List 2 Substances form the Groundwater Directive;

- Collates data systematically;

- Delivers information rich output(s);

- Categorisation of methods of measurement of various risk analysis parameters into six groups (listed below in Section 8.4.2);

- Ability of running union queries in order to measure a parameter's five values which are highest and lowest maximums, average of all most likely / mean values, highest and lowest minimums (more details below in Section 8.4);

- Processes the whole risk assessment exercise algorithmically and categorically, not just in terms of data collation but also methods of measurement and their results as well as the final outputs of the risk assessment exercise;

- Capability of establishing risks at three levels / degrees which are worst case, most likely and least bad scenarios (elaborated in Section 8.4 below);

- Risk assessors and managers can communicate to other relevant stake holders who may not necessarily have any background in risk assessment and management, for instance, legislators, lawyers, regulators, landfill companies, landfill operators / managers, engineers, designers, developers, local planning authorities, councils, funders, lenders and contractors.

8.4 Other Novel Features of the RAM

Some extra novel features of the RAM are listed below which enable the RAM to diversify on its ability to cope with different landfill systems and scenarios.

8.4.1 The Three Themes of Risk Degree

The Risk Assessment Methodology (RAM) and its computer model are developed in a systematic way that there is allowance to render three types of results at various intermediate stages of a risk assessment process and eventually three types of scenarios towards the end of the process. These three types of results are Maximum, Most Likely / Mean and Minimum. Correspondingly, the three types of scenarios are:

1. Worst Case Scenario;
2. Most likely or Average Scenario; and
3. Least Bad Scenario (which is an entirely new dimension developed in this study to make use of minimum values and thereby enable a risk assessor to establish the extreme ends of the risk range, i.e. worst and least bad, and the position of the most likely on this scale).

8.4.2 Six Categories of Methods of Measurement

This research study appreciates that a risk assessment process for landfills comprises numerous parameters from various subjects. There is more than one method of measurement and / or means available to establish values of these wide-ranging parameters quantitatively. Thus, the RAM produced in this research is designed to accommodate results from all possible methods by categorising them into six groups. These groups are:

1. Organisation / Authentic body;
2. Field experimental method(s);
3. Laboratory experimental method(s);

4. Empirical method(s);
5. Typical values (for instance, typical leachate constituents of municipal waste landfill in the UK); and
6. Judgement (from relevant experts, such as meteorologists, geologists, hydrogeologists, particularly when the site-specific information is lacking).

8.4.3 Quantitative Approach

There are three types of risk assessment approaches. These are quantitative, semi-quantitative and qualitative. The RAM produced in this research study is based on the quantitative approach rather than the other two.

8.4.4 The Holistic Nature of the RAM

The main focus of this research study has been the coverage of holistic nature of the process of risk assessment for landfill leachate. Therefore, the RAM is developed to encompass all RAM items without engaging with them to full depth as individuals. The RAM Model is designed covering the depth of these items just as far as it was necessary to achieve the functionality of the model from the start to end. Thus, the RAM / model addresses the 'wholeness' not in terms of the 'depth' but the 'breadth' encapsulating all parts, sub-parts, modules, sub-modules and parameters that may engage in a risk assessment.

8.4.5 Background / Initial Concentrations

Background or initial concentrations of pollutants are given considerations. For instance, final pollutant concentration at a receptor / target (TCf) is to take into account not only the pollutant concentration reaching or taken in by the target (Intk C) but also the background or initial concentration in the target boundaries (TCi), if any. The same approach is also applied to exposure media.

8.4.6 Unlimited Number of Landfill Scenarios

There are an unlimited number of landfill scenarios which this work has successfully categorised into certain groups. Examples of these groups are as follows. Coverage of post, in and pre-operation stages of landfills; addressing of spatial and temporal variation via statistical descriptions; defining the size of a region in which a given landfill is situated. These groups are addressed to the possible best level within the scope of the research undertaken.

8.4.7 Aggregation

The RAM has been designed to have attributes, which allow aggregation of individual hazard indices as well as individual risks to different receptors posed by different hazards via different pathways. These are referred to as Total Hazard Index (THI) and Total Risk (TR), respectively. The aggregation approach is also applied to sum up individual exposures via the four individual exposure routes.

8.4.8 Penta M / 5M's Concept

An entirely new concept is developed on the basis of statistical descriptions and named Penta M or 5 M's. These five M's are: highest maximum, lowest maximum, average of all most likely or mean values, highest minimum, and lowest minimum. In this way the range of 'conservativeness' can be covered from possible least minimum to possible most maximum values for various RAM parameters.

8.5 Outcomes of the Research Study

8.5.1 Potential Benefits

Whilst risk assessment is increasingly becoming a legal requirement, the outputs of the research study which mainly comprise a framework of the RAM and the corresponding computer model can quantitatively provide an even stronger base for risk controls /

reductions and consequently carry out risk management more effectively. This research work is also useful in underpinning the Environmental Impact Assessment and Statement, which is a legal requirement for landfills and identifies impacts on the environment, both natural and built in a much broader sense. Thus, this study may well indirectly play an effective role in landfill planning permission and in design, construction and hazard mitigation measures. Due to the degree of holistic nature that the RAM framework offers, the issues raised by the Water Framework Directive and Habitats Directive will be taken into account. These issues include surface water, natural habitats, aquatic and terrestrial flora and fauna. This study can also be useful to expand on in a number of directions not only to further enhance the current status of the outputs produced in this research work but also to reproduce for other environmental issues such as landfill gas, contaminated land, and radiation. This is described briefly in the section below.

8.5.2 Further Research Potentials

An additional outcome of the research task undertaken is that this research has assisted in establishing a range of further research potentials to be looked into by successors. Some of these research potentials are listed below:

1. At the moment the RAM model can deal with one set of receptor / target and pathway and all hazards in one iteration. For other combinations of targets and pathways the model has to be run to perform as many iterations. In future, the model can be developed to take all combinations of pathways, targets and hazards in a single iteration. Correspondingly, Equations 5.6, 5.7 and 5.8 (in Chapter 5) can be enhanced to depict this.

2. The RAM / model can take either the most likely values or mean values. Not both of them are allowed in the model at the same time. Thus, in future the model can be developed further to allow for both types of values at the same time. This way it will be possible to determine both the most likely as well as the mean risk scenarios simultaneously.

3. Similarly, other statistical descriptions such as standard deviation and median, which are not yet part of the model, can be assembled to the model in future development to render it yet even more statistically sound. This, consequently, will further enhance the addressing of uncertainties in various RAM parameters.

4. Like the 5M's concept is applied to the hydrology parameters (such as interception and precipitation), this approach needs to be developed for other parameters of the rest of the seven modules of the Baseline Study such as hydrogeology, geology.

5. Similarly, the way the RAM model can workout 5M's values for the hydrology parameters when a button is clicked, the same 'workout button' option can be employed for other modules and / or sub-modules of Exposure Assessment and Concentration Assessment. For instance, Exposure Quantification (Ex Quan), Target Final Concentration (TCf); Target Initial Concentration (TCi). These modules and / or sub-modules do have the facility of maximum, minimum and most likely / mean but the model does not work these out within the model, rather the user has to determine these outside the model and then feed the results back into the model.

6. If (highest) maximum leachate quantity is considered in a risk assessment for working out worst case scenario in the context of leachate quantity hazard, this may mean entirely the opposite in the consideration of pollutant concentrations in terms of leachate quality hazards. This is because the more the leachate the less the pollutant concentrations. In other words, maximum leachate quantity would mean minimum concentrations of pollutants in the leachate, which is less risky matter than if the leachate's least quantity is considered rendering highest pollutant concentrations. On the other hand, if least leachate quantity is considered then it may be comparatively slower to reach a given target due to less pressure head, consequently probably less risk. This dilemma needs to be researched further. However, at this stage it is left up to risk assessors which way they want to consider.

7. Further development of the Migration Assessment section of the RAM model is needed. For instance, Migration and Attenuation modules and their sub-modules can be expanded in terms of their functionality and interaction with other RAM items. Similarly, in the Exposure Assessment section of the RAM, (chain) links of pathways before exposure media (i.e. pre-exposure media) need further development; an example of which would be integrating the CEP (Conceptual Exposure Pathway) approach into the RAM model.

8. Although, Uncertainty Assessment has been addressed in this research study to an extent, particularly in the context of its position in the RAM framework, there is considerable room to further enhance this aspect of the methodology and model for various risk assessment parameters, especially from the perspective of being able to estimate and address uncertainties in an objective manner. The induction of more statistical descriptions such as standard deviation and median (indicated above) could be one of the ways forward.

9. For a quality hazard like pH there is a limitation in the interpretation of the HI value in the 'HI_Measuring' form in the RAM computer model (as explained in Chapter 6, Section 6.9, under the heading 'Exception – HI interpretation for quality hazards like pH'). This limitation needs to be mended in any future development such that the HI figure in the 'HI_Measruing' form of the model turns red only when the HI ratio falls outside the safety band across the 7.5.

10. Leachate quality hazards are identified in the H Iden Quality module. Unlike leachate sampling which is possible when a landfill site already exists, if this identification is to be anticipated, for instance, from waste types of a landfill yet to exist. Then the information will need to be derived from the sub-modules such as Site History and Site Documentation of the Site Management module. Therefore in future, the RAM model can be furthered by designing inter-link between the H Iden Quality module and these relevant sub-modules of the Waste Management module. Similarly in the sub-module Source Concentration Assessment (Sorc C) for concentrations to be anticipated from types, constituents and amounts of wastes to

be landfilled or landfilled in the past, these sub-modules of Site Management require to be inter-linked with the Sorc C sub-module as well.

11. This point is for the Target Concentration – Final (TCf) section of the RAM model. If a living environmental receptor or target is under consideration, e.g. a human, fish or bird, then the 'equivalent' background concentration (TCi) in the receptor body has to be worked out and yet in the same unit as that of Intake Concentration (Intk C). This is in order to be able to add the two figures together to obtain the Final Target Concentration (TCf). To establish this equivalent TCi value alone or even to calculate TCf altogether in this way is an area needing further research.

12. In the Target Concentration – Final (TCf) section of the RAM model for scenarios containing non-living environmental receptors, when two streams meet spatial and / or temporal dilution may take place. The examples of meeting of such streams are leachate entering an aquifer; an aquifer falling into a surface watercourse or even leading to a water abstraction well; dilution within the receptor itself like a river. Such temporal and / or spatial dilution aspects need to be researched and integrated into the model to render it more robust and precise for various sets of meeting streams.

13. Only the Risk Assessment (RA) forms the remit of this study and not the Risk Reduction (RR). The latter, which comprises Risk Evaluation (R Eva) and Risk Control (R Cntrl), can be developed in order to accomplish the remainder of the Risk Management.

14. Once the whole of the Risk Management process has been prepared in the form of a methodology and computer model, this can be furthered to form an 'expert system' by introducing artificial intelligence. Such an expert system can assist making risk control decisions automatically.

15. The holistic RAM and model, which currently is only landfill leachate, can be reproduced for landfill gas as well as degraded waste in a landfill body. Then the

risk assessment methodologies of these three phases; that is leachate (which is a liquid), landfill gas and more or less degraded waste (which exists in a solid state), can be put together to form an even more holistic risk assessment methodology and a corresponding computer model.

16. The knowledge-base computer model of RAM contains databases to a limited extent, for instance, List 1 and 2 substances from Groundwater Directive. There is huge room to add more databases to various RAM items, which may be used particularly as representative data when site-specific data are not available. For instance, databases of methods of measurement of various RAM items can be added into the model.

17. The RAM model can be enhanced to pictorially / visually simulate the hydrogeological conceptual model of the landfill site being assessed, once all the Baseline Study modules have been processed. This automatic formation of the conceptual simulated model in visual form can be shown with arrows up and down and in and out of landfill body for various parameters with tags indicating maximum, most likely and minimum values. Examples of such parameters are precipitation, interception, groundwater ingress, percolation, leachate generation per annum, groundwater fluctuation, landfill design and engineering.

18. The visual / pictorial conceptual simulation indicated above can also be even further enhanced to show all potential targets / receptors and pathways not only on-site but also off-site.

19. The RAM model can allow one form to print at a time. The printing feature of the model needs to be developed such that the whole risk assessment exercise once completed can be printed off in one run and yet in a systematic and sequential manner. A summary of the whole risk analysis process for a given landfill to which the RAM is applied, can also be a very good idea. This summary should be both technical as well as non-technical, or maybe two summaries one technical and the other non-technical thereby covering wide and diverse range of stakeholders.

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APPENDIX A

Refereed Journal Publications

The published papers cited below have been removed from the e-thesis due to copyright restrictions:

- **Butt, T. E.; Lockley, E.; and Oduyemi, K. O. K. 2008, 'Risk Assessment of Landfill Disposal Sites - State-of-the-art', Waste Management International Journal, Vol. 28, Number 6, p. 952 - 964.**
- **Butt, T. E.; Davidson, Henry A.; and Oduyemi, K. O. K. 'Hazard Assessment of Waste Disposal Sites: Part 1 - Literature review ', International Journal of Risk Assessment and Management (IJRAM), accepted February 2007, in press.**
- **Butt, T. E.; Davidson, Henry A.; and Oduyemi, K. O. K. 'Hazard Assessment of Waste Disposal Sites: Part 2 - A holistic approach', International Journal of Risk Assessment and Management (IJRAM), accepted February 2007, in press.**
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- **Butt, T. E. and Oduyemi, K. O. K. 2003, 'A Holistic Approach to Concentration Assessment of Hazards in the Risk Assessment of Landfill Leachate', Environment International Journal, Vol. 28, Issue 7, p. 597 - 608.**